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Density as a cost driver in Naval submarine design and procurement

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THESIS

DENSITY AS A COST DRIVER IN NAVAL SUBMARINE DESIGN AND PROCUREMENT

by

Benjamin P. Grant

June 2008

Thesis Co-Advisors: Daniel A. Nussbaum
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13. ABSTRACT (maximum 200 words)

This thesis examines density reduction as an alternative to weight or size reduction when decision makers seek options for lower-cost submarine designs. The parameter density measures how tightly systems and equipment are placed within a hull structure. To address design characteristics unique to submarines, this research focuses mainly on submarine design and procurement—although the general concepts are applicable to surface ship designs and may be applied more broadly. Based on an examination of density as it relates to cost, this research indicates that: (1) the use of weight-reduction policies as a means to reduce cost have often generated the opposite effect; (2) increased cost, schedule and performance risk and an improper mix of design capability and flexibility are the inevitable outcomes of unnecessarily dense designs; and (3) Arc-permeability and Internal Density, measures developed for this research, are sufficient approximations of how tightly systems and equipment are placed within a compartment. Indeed, they may reveal how density represents a significant and previously underemphasized, if not unexplained, driver of historic submarine cost-growth in excess of inflation.

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DENSITY AS A COST DRIVER IN NAVAL SUBMARINE DESIGN AND PROCUREMENT

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Submitted in partial fulfillment of the
requirements for the degree of

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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ACKNOWLEDGMENTS

> Trust in the LORD with all your heart, and lean not on your own understanding; in all your ways acknowledge HIM, and HE shall direct your paths
>
> - PROVERBS 3:5-6, NKJV

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I. INTRODUCTION

A. PURPOSE OF STUDY

The purpose of this study is to reveal the inadequacies of weight as a parametric cost estimator in modern U.S. Naval submarine design and procurement. Density reduction is examined as an alternative to weight or size reduction when decision makers seek options for lower-cost submarine designs. To address the unique issues associated with submarine density, the main focus of this research is on submarine design and procurement—although the general concepts are applicable to surface ship designs and may be applied more broadly. If a positive correlation between submarine density and cost can be found, it is conceivable that a larger, less dense submarine could be designed and built more affordably than a smaller, more complex design.

B. PROBLEM

Roy Burcher and Louis Rydill, in their book *Concepts in Submarine Design* (1994) explain, "There is a temptation to speculate whether submarines would be cheaper to build if they were made larger and less congested, but although the instincts of many who have been involved in design and building submarines lead them to believe that could be so, it is difficult to prove or demonstrate" (p. 226).

The primary difficulty to date in demonstrating a relationship between density and cost in submarines has been a lack of analogous submarine designs capable of generating the necessary data to underpin a statistical cost comparison. Now, a sufficient number of modern submarine designs exist with cost and design data in sufficient detail for researchers to *begin* to demonstrate the relationship between submarine density and cost.

The researcher selected six U.S. Naval submarine designs (for reasons explained in Chapter III) to investigate the notion that density may be acting as a cost driver in naval submarine design and procurement. The submarine designs selected are:

- USS Sturgeon (SSN 637)
- USS George Washington (SSBN 598)
- USS Ohio (SSBN 726)
- USS Los Angeles (SSN 688)
- USS Seawolf (SSN 21)
- USS Virginia (SSN 774)

Cooperation, assistance and data were provided by designers, cost estimators, engineers and acquisition professionals at Naval Sea Systems Command (NAVSEA) Cost Engineering & Industrial Analysis (05C) and Submarine Advanced Concepts Division (05U), Strategic Systems Programs (SSP), Program Executive Office (PEO) for Submarines, Naval Center for Cost Analysis (NCCA), General Dynamics' Electric Boat (GD/EB) and Northrop Grumman Shipbuilding (NGSB). To preserve the non-proprietary nature of this research, the results are presented such that actual values of sensitive information are masked.

Many recent ship and submarine design decisions have been made on the assumption that cost per unit weight is fixed and that the cost of future designs will align with historic trends without adjustments for variations in design complexity or congestion. This assumption has led to the treatment of weight as an independent variable and its management as an indirect means to manage cost. This research will attempt to reveal that cost per unit weight can vary with a vessel's complexity—of which density may serve as the proxy.

By breaking this direct link between weight and cost, this research would lay the foundation for several innovations in submarine acquisition, to include the following:

1. Contribute to conversations about the correct mix of capability and flexibility in a design by allowing informed decisions to be made regarding the space required and the cost to incorporate design flexibility, modularity, maintainability, reliability and life cycle cost-efficiency into future submarine designs.
2. Highlight the importance of a deliberate and carefully guarded acquisition strategy and provide a means to reconcile seemingly contradictory strategic design goals.
3. Enable an opportunity for meaningful comparisons of naval ship and submarine designs of various types, sizes and levels of complexity.

C. ORGANIZATION

This thesis is organized into five chapters. Chapter I introduces the purpose of the study. It also highlights some problems that have previously prevented a thorough investigation of a potential relationship between density and cost in submarine design and procurement. The subsequent three chapters discuss background information, research methodology and research results. Chapter V provides a summary of findings, conclusions and recommendations.

1. Chapter II—Background

The information for this chapter was gathered by way of a literature review and interviews with experts in the fields of submarine costing, design and procurement. In all, 54 interviews were conducted with individuals affiliated with the following organizations:

- Congressional Budget Office (CBO), Washington, DC
- Congressional Research Service (CRS), Washington, DC
- Cost Analysis Improvement Group (CAIG), Arlington, VA

- General Dynamics’ Electric Boat Division (GD/EB), Groton, CT
- Massachusetts Institute of Technology (MIT), Cambridge, MA
- Naval Postgraduate School (NPS), Monterey, CA
- Naval Reactors (NAVSEA 08), Washington, DC
- Naval Sea Systems Command Cost Engineering and Industrial Analysis (NAVSEA 05C), Washington, DC
- Naval Sea Systems Command Submarine Design and System Engineering (NAVSEA 05U), Washington, DC
- Northrop Grumman Shipbuilding (NGSB), Newport News, VA
- RAND Corporation, Arlington, VA
- Strategic Systems Programs (SSP), Arlington, VA
- Program Executive Office (PEO) for Submarines, Washington, DC

A standardized list of interview questions was used to facilitate discussions, although other topics were discussed consistent with the interviewees’ area of expertise and past experience. The standardized interview questions are provided in Appendix A.

Chapter II begins by discussing submarine sizing considerations. A comparison of an arrangement- versus a weight-driven design is provided. The submarine sizing considerations section closes with an overview of some strategies for weight and size management during the submarine design process.

A section on the advantages and disadvantages of weight-based cost estimates follows. The latter portion of this section reveals the need for a parameter that not only speaks to the size of a submarine design, but one that reveals how tightly systems and equipment have been placed within the structure. This section forms the theoretical basis for density as a cost driver.

The final section in Chapter II discusses the potential benefits of realizing the effects of density on cost. It contends that the right mix of capability and flexibility, a congruent acquisition strategy and a means to compare vessels of differing types, sizes

and levels of complexity by way of compensated gross tons (cgt) are all possible when the negative effects density can exert on cost are known and factored into the decision-making process.

2. Chapter III—Methodology

The Methodology Chapter describes the process by which data were gathered, normalized and used to investigate potential relationships between density and cost. The cost and hours data were provided by NAVSEA 05C. The design data were provided by NAVSEA 05U and GD/EB. Actual values have been masked to protect the sensitive nature of much of the data used.

3. Chapter IV—Results

The Results Chapter presents the three cost segments (Shipbuilder, Government-furnished Equipment (GFE) and End-cost less Other) and the two labor segments (Detailed Design hours and Production hours) plotted against the two density measurements (Internal Density and Arc-permeability)—for a total of ten plots. The curvilinear lines superimposed on the plots are notional. They are intended to show how the data relate to the theoretical relationship of density and cost.

4. Chapter V—Summary, Conclusions and Recommendations

Chapter V opens with a summary of findings. Next, the Conclusions Section suggests some possible applications of the findings for five groups or individuals responsible for various aspects of submarine design and procurement. Finally, the Recommendations Section proposes areas where the theory and potential applications of the theory could benefit from additional research.

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II. BACKGROUND

A. SUBMARINE SIZING CONSIDERATIONS

Explanations of the hidden complexities encountered when making submarine sizing decisions have been recorded in works by Jackson (1992, 1998), Burcher and Rydill (1994), Arentzen and Mandel (1960) and others. For example, according to Jackson:

> The volume of the hull of the submarine is fixed by the weight of the submarine. If more volume is mandatory, it can only be provided by making the submarine larger, but this will increase the amount of lead to be carried and reduce the speed if the same power is provided. If the power is increased in order to meet the speed requirements, the submarine will grow even larger. The skill and experience of the designer is put to a crucial test in making a satisfactory design. (1998, p. 11)

This quote only begins to reveal the interdependent nature of the many decisions that are made during submarine concept development and design phases; it serves to emphasize the need to strike a balance between size and capability.

It is not the goal of this research to comprehensively describe the many and varied interactions between space and weight that have been documented in the above mentioned and other works; rather, the submarine sizing considerations recounted here serve to reveal the following:

- Initial submarine sizing decisions are a leading determinant of the ultimate life cycle cost of a submarine, and the cost risk associated with undercalling the required volume is disproportionately high.
- Constraints placed on the overall size or weight of a submarine design as a means to reduce procurement costs will tend to produce the opposite effect, while encouraging behavior that can lead to reductions in design flexibility, maintainability and reliability.
- More space than has traditionally been made available is required as submarine designs incorporate modular construction techniques, open systems architecture and commercial off-the-shelf products.

In the words of Burcher and Rydill:

> Other things being equal, a smaller submarine with the same capability as a larger one should have the operational edge; and there is a temptation to believe that it would be cheaper to build and operate. If correct these would be benefits, so why do we qualify with the phrase “other things being equal”? The reason is that a submarine is palpably the most dense and complex of marine vehicles, and this is reflected by the high labour costs involved in fitting them out under very confined conditions; to go further in squeezing up on the contents could become counterproductive and almost certainly push up building costs rather than reduce them, as well as making maintenance in service and the work of refitting more difficult and probably more costly […] The aim is not to produce the smallest possible submarine for the allotted tasks, but one which represents a good compromise between operational effectiveness and least through life cost overall; that then is the size determinant. (Burcher & Rydill, 1994, p. 67)

1. Arrangement- vs. Weight-driven Designs

As previously mentioned, submarines are the densest of all marine vehicles (Burcher & Rydill, 1994). In fact, it is their density that allows them to perform their most fundamental function—submerged operation. On the surface, submarines achieve a density less than that of water by filling the submarine Main Ballast Tanks (MBT) with air, thus creating a Reserve of Buoyancy (ROB). In order to submerge, the submarine allows the MBTs to fill with water, eliminating the buoyancy reserve. This satisfies Archimedes’ Principle, which states that the weight of a displaced fluid is directly proportional to the volume of that displaced fluid (Heath, 1897). Thus, for a submarine to operate fully submerged, it must be capable of achieving a density equal to that of the fluid in which it intends to operate.

Nominally, the submarine hull and structural components contribute nearly half of the weight required to achieve the submergence weight for a given submarine volume. The remaining weight is contributed by the various systems, equipment and ballast attached to or installed within the submarine hull. The significant contribution to the required submergence weight by the submarine hull and structural components is driven largely by the following two factors:

- The hull weight is the natural outcome of the need to withstand the extreme hydrostatic forces experienced at the maximum design operating depths.
- Due to the relatively low density of installed systems and equipment, the dense hull brings the density of the overall design into balance.

Therefore, when considering the ultimate size of a submarine design, designers exert considerable effort in achieving harmony between the submarine hull structure and its contents.

The relationship between a submarine hull structure and its contents will generally fall into one of two broad categories: arrangement-driven or weight-driven. If the relationship between the hull structure and the components placed within are such that the interior volume is used up prior to the overall design reaching its submergence weight, the design is said to be "arrangement-driven." Additional weight, usually in the form of lead ballast, must be added to an arrangement-driven design in order to submerge. Arrangement-driven designs may be synonymously referred to as volume- or space-driven. Alternatively, if the relationship between the hull structure and the components placed within are such that submergence weight is achieved prior to using up the available space, the design is said to be "weight-driven." Lead ballast or weight in some other form must be removed in order to add additional items to a weight-driven design. Figures 1 and 2 provide a visual illustration of the difference between arrangement- and weight-driven designs.

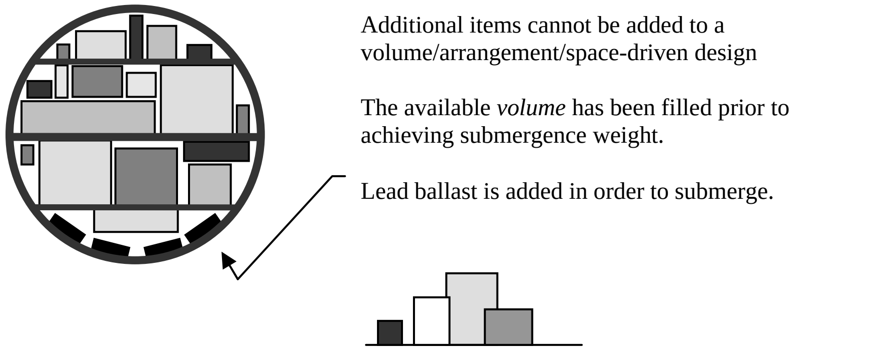


Figure 1. Volume/Arrangement/Space-driven Design

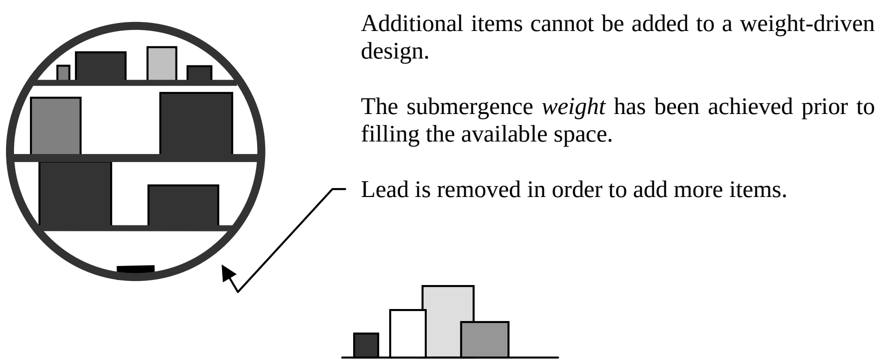


Figure 2. Weight-driven Design

There is a general sense that a design is in harmony when the hull weight and associated diving depth have been adjusted to the point at which the useable internal volume is just sufficient to accommodate the space required by the installed systems and equipment (Burcher & Rydill, 1994). Designing for a deeper diving depth would require designers to adopt a thicker/heavier hull to counter the proportional increase in hydrostatic forces experienced at deeper depths. This would necessitate a larger internal volume to restore the proper space/weight relationship to make neutral buoyancy

possible. If the space requirements for the installed systems and equipment remained unchanged, the volume required would be less than the volume made available by the heavier/larger/deeper diving hull. The weight needed to achieve neutral buoyancy would be achieved with space to spare, and the resulting design would be limited by weight. It is likely the customer would consider this an inefficient use of space, and an analysis of tradeoffs would drive the design back toward an arrangement-driven scenario. It is for this reason that for the majority of submarine designs, decisions regarding diving depth, hull material, margin ballast and overall size are made such that the resulting initial design will be arrangement-driven (Burcher & Rydill, 1994).

According to Burcher and Rydill (1994), one good strategy to create harmony between the submarine hull and its contents is to begin by treating the design as arrangement-driven (Burcher & Rydill, 1994). Once the space requirements for the installed systems and equipment are determined, the hull is designed to accommodate them. Trade-offs between the resultant diving depth, top-end speed, required hull material, etc., would be performed on a cost-benefit basis. The resulting design should possess performance parameters within customer expectations, while avoiding large amounts of unusable space caused by a premature achievement of submergence weight. Once fixed, the hull size and internal volume can no longer be used to achieve the proper space/weight balance.

During the design effort, a space and/or weight margin policy is employed—whereby allowances for growth in size and/or weight requirements will not cause the design to become either arrangement- or weight-driven prematurely. According to Burcher and Rydill:

> If, when a new submarine design was complete and the first-of-class boat built, the weight margin had not been entirely consumed, the amount of solid ballast to be stowed on board would be larger than required. Since the design would generally have been space [or arrangement] driven the submarine would not be larger than it need have been, just more stable. If, exceptionally, the design was weight driven the submarine would, in the circumstances being discussed of an incompletely consumed weight margin, be larger than it need have been. Either way, the outcome would be a small penalty to pay for the insurance afforded by weight margin policy against the more serious hazards of undercalling on weight. (Burcher & Rydill, 1994, p. 66)

The danger of becoming weight-limited prematurely in the submarine design process highlights the importance of reasonably conservative weight estimates and weight margins at the design onset. If a design must incorporate greater flexibility—having the capacity to incorporate future technologies—then the need to ensure the availability of weight and space margins extends past the end of the design effort and well into the service life of the submarine. Indeed, if space and weight margins are entirely consumed during the design effort, the resultant submarine design may be capable of accomplishing the tasks for which it was designed, but wholly incapable of incorporating new technologies in the future. An argument is made in Chapter II that suggests current rates of technological and tactical change imply that sustained suitability is only possible if sufficient space and weight margins survive the initial design process to allow for configuration changes throughout the design life of the hull. This should be considered prior to employing strategies of submarine design (such as those by Burcher and Rydill) that were developed in an era when the need for current capability overshadowed any perceived need for future design flexibility.

2. Weight Management

Careful and meticulous weight management and accounting is critical to any successful submarine design effort. Not only must the design achieve a specific weight target for the chosen volume, the weight must be distributed such that the centers of gravity and buoyancy are in proper absolute and relative positions for hydrostatic stability reasons.

If a surface ship design exceeds its target weight, the resultant deeper draft and performance penalty will likely be tolerable. However, if a submarine design exceeds its weight target as dictated by the chosen volume, the consequences can be ruinous. If all margins have been exhausted, there is no reserve buoyancy from which to borrow—as is the case with surface ships. Permanent ballast must be removed, causing potentially unacceptable compromises in hydrostatic stability. The only way to fix such a condition is to increase buoyancy. The only option typically available to the submarine designer

when such issues are uncovered is to lengthen the submarine hull. Thus, the impact of the changes required to recover from a design that is overweight for its associated hull volume can be far-reaching and costly.

Given the penalty for allocating insufficient weight margin, designers should carefully determine the right weight margin quantity. Unfortunately, according to Peter Canning, Manager of Naval Architecture at GD/EB, selecting the proper quantity of margin lead defies statistical analysis. According to Canning, it is more a function of "How much money do you have in your pocket?" (Canning, 2008, March 25). Burcher and Rydill also admit that the amount of margin lead for which to budget is a policy decision (Burcher & Rydill, 1994).

There are several reasons to minimize the amount of weight margin allocated to a design. First, each pound of margin lead represents an opportunity cost of one pound of current capability. Additionally, it is difficult to predict where the margin lead will ultimately be needed, and misplaced margin lead could be considered wasteful and inefficient. Finally, the lead used is not necessarily cheap.

Conversely, the tendency to undercall eventual weight requirements is more likely. Also, increased design innovation leads to further increases in weight-estimate uncertainty. Finally, weight increases while in service are real and can be significant.

The following comments were made by Admiral Hyman Rickover as part of his testimony before Congress, published in *AEC Authorizing Legislation: Hearings before the Joint Committee on Atomic Energy* (1970).

> An academic reactor or reactor plant almost always has the following basic characteristics: (1) is simple, (2) is small, (3) is cheap, (4) is light, (5) can be built very quickly, (6) is very flexible in purpose, (7) very little development will be required (it will use commercial off-the-shelf components), and (8) the reactor is in the study phase; it is not being built now.
>
> On the other hand, a practical reactor can be distinguished by the following characteristics: (1) is being built now, (2) is behind schedule, (3) requires an immense amount of development on apparently trivial items, (4) is very expensive, (5) takes a long time to build because of its engineering development problems, (6) is large, (7) is heavy, and (8) is complicated. (p. 1702)

Therefore, given the tendency to undercall the weight required, the increased uncertainty of innovation, the reserve capacity required to incorporate changes while in service and in spite of the difficulty to do so; decision makers must condone sufficiently conservative weight margin policies as to avoid the disproportionate increases in cost, schedule and performance risk that result when weight margins prematurely expire.

3. Space Management

In submarine design, space can refer to volume, deck surface area or stack-up length—depending on the type of space that tends to be limiting the options of the designer. Like weight estimates, the identification of the true space required for various systems early in the design process is difficult and inherently inaccurate. Additionally, late-term design changes or middle-of-life upgrades require weight *and* space margin, sufficient in both quantity and location, to be executable. This would tend to advocate the use of a formal space-margin policy.

While Burcher and Rydill acknowledge a natural tendency toward and a theoretical logic intrinsic in the idea of a space-margin policy, they warn of practical difficulties in its implementation. Many small space allocations could be quickly garnished by local relaxations while several larger spaces may not provide the space where it is needed (Burcher & Rydill, 1994). As evidence, they cite the almost inescapable force of Parkinson's Law, which states that the space required for a design will always expand to fill the space available (Burcher & Rydill, 1994). Yet, regardless of the relative difficulty, and perhaps because of it, designers of any successful submarine design effort must manage the space occupied by items and take measures to ensure space is available when the needs of the design so dictate. Consequently, any constraint that would unnecessarily inhibit the realization of the optimal amount of space as dictated by the construction methods and the combined space requirements of the installed systems should be avoided.

4. Summary

Burcher and Rydill's commentary on the employment of weight and space margins in submarine design strives to create a framework in which a capable and

efficient submarine may be designed and built by mitigating the risks associated with the initial undercalling of size or weight. If plans are to employ a submarine design in its initial configuration throughout its design life, a first-of-class design with residual weight or space margins would be preferable, however, either of these would be considered wasteful nonetheless. On the other hand, if rates of technological change or volatility in the threat matrix dictate that a submarine design be capable of incorporating future technology or reacting to an emerging threat, weight and space margins that survive the initial design process may be the only means by which a submarine design may have the flexibility to adapt. Therefore, a submarine designed for flexibility and promising the lowest possible life cycle costs requires space and weight margin policies capable of producing a first-of-class submarine that is essentially *neither* space *nor* weight limited.

B. WEIGHT AS A COST DRIVER

1. Advantages

Weight-based, parametric cost-estimating relationships (CERs) have gained widespread use among reputable Congressional, independent and Department of Defense-affiliated agencies. The Congressional Research Service (CRS) has used weight-based CERs to justify their recommendations to Congress on matters relating to reducing the cost of ship and submarine designs. The Congressional Budget Office (CBO) has used them to explain current cost overruns. RAND Corporation has used weight as a proxy for design complexity in its analysis of ship and submarine cost escalation. Naval Sea Systems Command (NAVSEA) Cost Estimators use weight data routinely when costing large weapon systems. One reason for the widespread use of weight as a cost driver is that weight data tend to be readily available and highly accurate. But perhaps the most compelling reason has been the apparently consistent relationship between cost and weight over time.

a. For Congress

A Congressional Research Service (CRS) report entitled *Navy Ship Acquisition: Options for Lower-Cost Ship Designs—Issues for Congress* dated June 23, 2005, provides the following consolidated list of options for lower-cost attack submarine, aircraft carrier, and surface combatant ship designs:

- reduce ship size
- shift from nuclear to conventional propulsion
- shift from a hull built to military survivability standards to a hull built to commercial-ship survivability standards
- use a common hull design for multiple classes of ships (O'Rourke, 2005, p. 3)

According to the CRS report, the first option—reduce ship size—relies on an observation that, "for a given type of ship, procurement cost tends to be broadly proportional to ship size" (O'Rourke, 2005, p. 3). In essence, the CRS is treating cost per unit weight as fixed, and is equating weight with size. Given the cited link between weight and cost, their conclusion suggests that more size (or weight) will lead to higher costs. Thus, one way to lower costs is to reduce size. In a telephone interview with the researcher, Ronald O'Rourke (author of the above-mentioned CRS report) explained the CRS uses weight as a parametric cost estimator because weight data is what it has access to, and that weight has been shown to correlate well with cost in the past. More recently, Eric Labs of the Congressional Budget Office (CBO)—in a testimony to Congress on March 14, 2008—used weight-based parametric cost estimates to take issue with a number of Navy estimates on various ship programs (Labs, 2008). In essence, Labs and O'Rourke have reduced their procedure for predicting future ship costs and explaining present cost overruns to the results of a regression of cost and weight.

b. Among Independent Agencies

RAND Corporation published a report exploring cost escalation in U.S. Navy ships and submarines (Arena, Blickstein, Younossi, & Grammich, 2006). In it, they identified the following five drivers of ship and submarine cost divided into two broad classes:

- Economy-driven Factors
  - Labor
  - Material and Equipment
- Customer-driven Factors
  - Characteristic Complexity
  - Other Ship Features
  - Procurement Practices

Of the five identified cost drivers, characteristic complexity is the one that refers to how changes to basic ship features (e.g., displacement, crew size, number of systems) make them more difficult to construct. Light ship weight (LSW) was used along with power density as its proxy in multivariate regressions. LSW, or light displacement, is the weight of the ship (in tons) including all permanent items. It does not include variable loads such as crew, stores, and fuel. Power density is the power generation capacity of a ship divided by LSW. The reason cited as to why LSW and power density were used was their observed correlation with end-unit costs (Arena et al., 2006).

c. Within the Department of Defense (DoD)

Within the Department of Defense (DoD), weight-based cost estimation finds wide use as well. For example, according to the NAVSEA 2005 *Cost Estimating Handbook* (*CEH*), "Weight is the most consistent physical property that the designer is able to provide to the ship cost estimator. Therefore, the most common parametric form employed in ship cost estimating uses weight as the technical parameter" (NAVSEA 05U, 2005, p. 4-12). In fact, "the three-digit weight breakdown is at the core of the NAVSEA ship cost estimating process and is mandatory for a Class C budget-quality

estimate" (NAVSEA 05U, 2005, p. 6F-9). Additionally, "the basic construction category line of an end-cost estimate developed within the guidelines of the Ship Estimate Classification System always has a weight breakdown to support the estimate" (NAVSEA 05U, 2005, p. 6F-9).

d. Summary

Arguments for the treatment of weight as a cost driver and its advantages have been made; they are well known and are well understood by those who use them and receive their results. However, the nuances and the limitations associated with weight-based cost estimation are less often made; they are not as well known nor as well understood by those who use them, and especially by those who receive and often act on their results. These nuances and limitations are discussed in the following section. They serve to reveal the growing inadequacy of weight alone as a cost driver in submarine design and procurement. They also serve to highlight the dangers of managing weight as an indirect means of managing cost. Upon this foundation, a theoretical basis is formed for the incorporation of density as a means to better predict the effect various design decisions will ultimately have on submarine costs.

2. Disadvantages

Each of the organizations that use or advocate the use of weight-based cost estimates caution their audiences on the limitations and potential inaccuracy of such an approach. For example:

a. Within the Department of Defense (DoD)

The NAVSEA *Cost Estimating Handbook* states that, "While weight is the most commonly used technical parameter and has been shown in practice to provide good estimates, the cost estimator is encouraged to explore other available parameters to be used with or in lieu of weight" (NAVSEA 05U, 2005, p. 4-14). Additionally, "In those increasing number of cases in which weight may not be the best cost-estimating parameter; e.g., state-of-the-art lightweight materials or combat systems for which

suitable CERs have not been developed, the resourceful estimator is encouraged to seek out other parameters to enhance the cost estimate" (NAVSEA 05U, 2005, p. 6F-9). In fact, in the area of submarine design, the NAVSEA *Cost Estimating Handbook* reveals that a majority of the CERs used in developing submarine estimates are not weight-based.

b. Among Independent Agencies

RAND Corporation qualified its use of light ship weight (LSW) as a cost driver in ship and submarine procurement by noting that, "these relationships are associative and not necessarily causal. In other words, going to a smaller ship will not always result in a lower-cost vessel" (Arena, Blickstein, Younossi & Grammich, 2006, p. xv). Another RAND report cautions, "Some risk arises from the inherent uncertainty in making any kind of cost or schedule estimate for an action that has no real analogue" (Birkler, Schank, Smith, Timson, Chiesa., Goldberg, Mattock & MacKinnon, 1994, p. xxiii-xxiv).

c. For Congress

Although, Labs of the CBO frequently employed weight-based cost estimates in his previously mentioned congressional testimony, he gave just as many examples of instances in which special circumstances led to the breakdown of the relationship between weight and cost. For example, the following is a quote from his testimony: "Reflecting its more complex combat systems, the cost per thousand tons of the lead Ticonderoga was more than 60% higher than the cost of the lead Spruance, notwithstanding their many common hull and mechanical systems" (Labs, 2008, p. 19). Finally, O'Rourke with the CRS admits regarding his previously mentioned options for Congress that, "Lower-cost ship designs using these approaches will in most cases be individually less capable than the currently planned ship designs from which they are derived" (O'Rourke, 2005, p. 3).

d. Epiphany at Electric Boat

"Weight is great for [steel] plate," but not for much else, according to Dave Bergheimer, a GD/EB Cost Engineer (2008, March 25). During an interview with the researcher, he discussed an epiphany of sorts that occurred in the late 1960s as Electric Boat transitioned from building Sturgeon Class submarines to designing and procuring the Los Angeles Class. Cost estimates were off—in part because the weight of electronics from Sturgeon to Los Angeles went down, but electronics costs rose significantly. This triggered a revolution in how Electric Boat performed its internal cost estimates. In essence, it discovered that cost per unit weight was becoming increasingly variable and heavily influenced by technology, acquisition environment, industrial base and other factors. Such factors had, to date, lacked the volatility required to disrupt the theoretical basis for the broad-based application of weight-based cost estimates. In the time since, the situations where weight-based cost estimates remained the preferred costing method steadily declined to the point where today, GD/EB uses weight based CERs for little other than steel plate costing. The cost engineers and naval architects at Electric Boat expressed a concern that alternatives to weight-based cost estimates have not been fully embraced elsewhere.

e. Premature Obsolescence

According to the previously mentioned CBO testimony (Labs, 2008, March 14), 14 of 18 recent ship classes have been decommissioned, on average, due to obsolescence prior to reaching their design end of life. This trend reveals a need to design for increased flexibility—which often means incorporating weight and space margins so that a hull designed to last 30-50 years can remain relevant. For example, over a 20-year period, the Los Angeles Class gained 60 pounds per day (on average) due to upgrades and configuration changes. These additions had to be offset by the removal of margin lead such that the overall weight and centers of buoyancy and gravity could remain within the constraints necessary for a hydrostatically stable design. Based on the locations where additional systems and equipment would likely be installed (above the centers of gravity and buoyancy) and the location of lead capable of providing an offset

(below the centers of gravity and buoyancy), the Los Angeles Class has essentially transitioned from arrangement-limited to weight-limited, preventing the economical addition of additional capability. If future submarine designs are made smaller and lighter, sufficient weight and space margins may not exist—leading to a premature transition to a weight-limited design and ultimately causing the submarine hull to outlive its tactical usefulness.

f. Moore's Law

Moore's Law—first postulated by Gordon E. Moore in April 1965 in an article in the *Electronics Journal* entitled, "Cramming More Components onto Integrated Circuits"—is based on an assertion that the number of transistors that can be economically placed on an integrated circuit will approximately double every two years. The theory behind Moore's Law represents a powerful analog to the potential interaction effects between a submarine hull and its contents.

According to Moore:

> For simple circuits, the cost per component is nearly inversely proportional to the number of components, the result of the equivalent piece of semiconductor in the equivalent package containing more components. But as components are added, decreased yields more than compensate for the increased complexity, tending to raise the cost per component. Thus there is a minimum cost at any given time in the evolution of the technology. (1965, p. 2)

This principle is illustrated in Figure 3 on the following page.

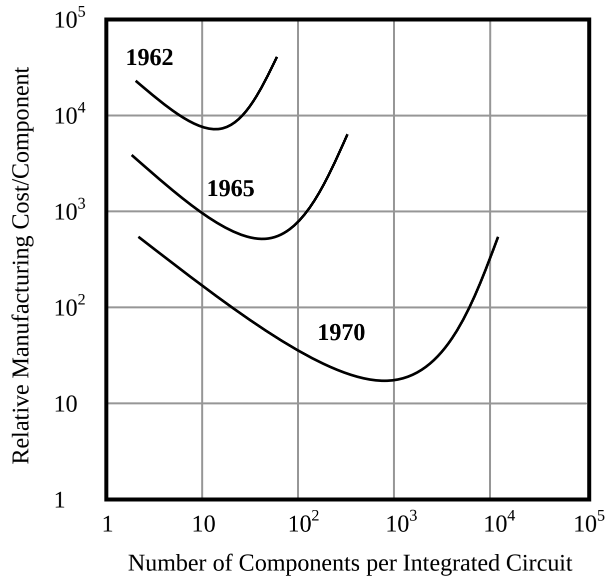


Figure 3. Range of Manufacturing Costs per Component versus the Number of Components per Integrated Circuit (From: Moore, 1965)

The number of components per integrated circuit is analogous to density as it is defined for this research. The relative Manufacturing Cost per Component is analogous to the cost per capability delivered—a metric difficult to quantify, but can be qualitatively inferred. If the analogy holds, as the quantity of systems and equipment installed within a submarine hull increase, the cost per capability provided will decrease due to the fact that the hull costs are spread over more capability. However, eventually the cost incurred by exploring creative ways to further increase the quantity of installed capability will grow at a rate greater than the rate of capability increase, and the cost per installed capability will rise. Therefore, for a submarine design, there exists some quantity of installed systems and equipment that minimizes the cost per delivered capability. Further, this cost-optimized point does not correspond to the maximum that current technology is capable of achieving.

Beyond the analogy between Moore's Law and density as a cost driver, what Moore's Law has meant for ships and submarines—such as the Arleigh Burke Class destroyer and the Los Angeles Class fast-attack submarine—is that the large and heavy

electronics installed in the 1970s and 1980s have been replaced with today's much smaller and lighter equipment. Such advancements acted as space and weight margins for future modification and upgrades as new technology became available.

Over the next 30 years, however, there are reasons Moore's Law should not be relied upon to as a means to realize design flexibility. For example, the thermal envelope and associated cooling requirements are becoming the limiting factors in adding technology to spaces provided by shrinking electronics. Additionally, standardized electronics spaces, such as the Structurally Integrated Enclosures (SIEs) in the Virginia Class, fix the volume within which electronic systems may be installed. Given that weight and space margin policies have benefited from electronics shrinkage in a way that may not be sustained into the future, increasingly deliberate methods should be employed to preserve the capacity to incorporate emerging technology.

g. Deck Surface Area

The chart depicted in Figure 4 shows deck surface area per volume for various hull diameters. According to Jeff Phfister at NGSB (2008, February 18), designing the interior spaces of a submarine is largely a two-dimensional problem, driven by the amount of deck surface area available. Thus, submarine designers strive to maximize the amount of useable deck surface area per given volume. In fact, maximizing deck surface area is a major determinant in the selection of a submarine hull diameter. What is evident from Figure 4 is that for a given number of decks, the deck surface area is maximized on a per-volume basis at the minimum hull diameter. The hull diameters for the submarines under consideration are indicated on the chart.

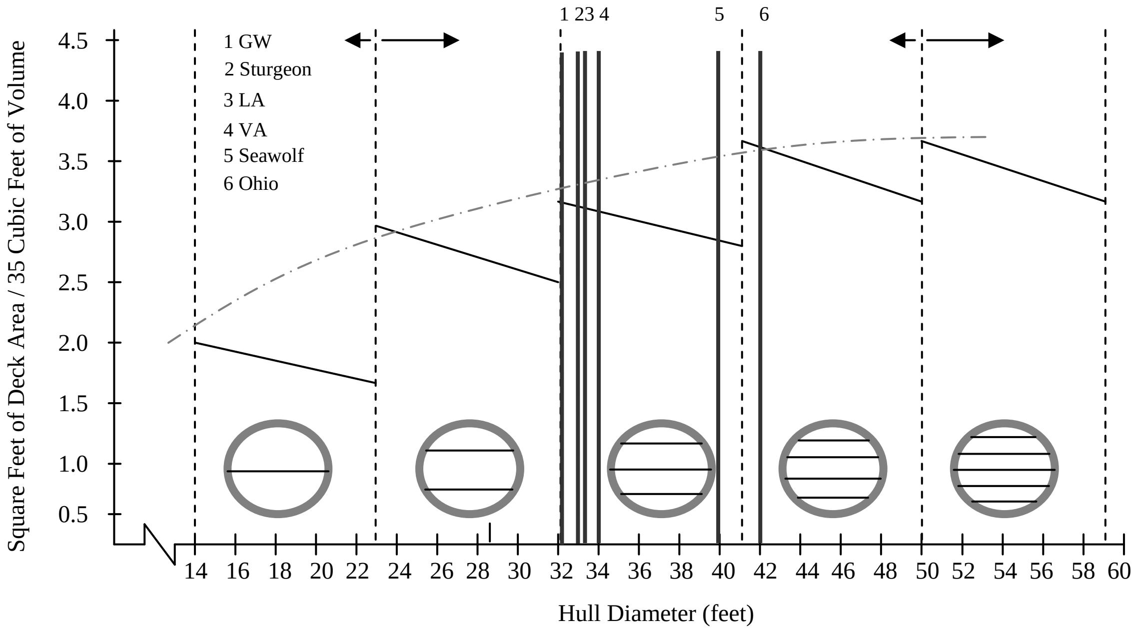


Figure 4. Deck Surface Area per Pressure Hull Volume for Various Hull Diameters (After: Joubert, 2006)

What is not immediately evident on the above chart is that the locations of the local maxima are not fixed, but rather are dependent on the construction method. Modularity demands an increased hull diameter to accommodate the added space that modular systems and construction methods require. Submarine designs have tended toward more modular designs, as have hull diameters—but this is not to say that they haven't done so under constant opposition from proponents of the notion that the smallest diameter yields the highest deck surface area per volume. When submitting its diameter recommendation for the Virginia Class submarine, of 33, 34 or 35 feet, GD/EB recommended 34 feet. Knowing what its designers know now and given the opportunity, GD/EB designers conceded 35 feet may have been preferable from a producibility, habitability and ultimately a life cycle cost perspective (Canning, 2008, March 25).

h. Hydrodynamic Drag

Hydrodynamic drag is the force a submarine must overcome to propel itself through the water. It is made up of pressure drag and skin friction. The total hydrodynamic drag for a given submarine volume varies with the ratio of length and diameter (L/D), as shown in Figure 5. Tear drop- or Albacore-shaped hulls experience minimum drag at an L/D between 6 and 7 (8 with appendages) (Joubert, 2006).

Design decisions regarding submarine length are almost entirely driven by the minimum stack-up length of components that must be placed low and along the longitudinal centerline of the hull. Submarine diameters are typically minimized as to achieve the maximum deck surface area per volume (per Figure 4) or based on some other limiting component. When the minimized length is combined with the minimized hull diameter, a suboptimal L/D results.

The L/D is driven further from the optimum when designers undercall ultimate weight of the installed systems and equipment and then design requires more interior volume to compensate. Often the only way to deliver the additional volume is to lengthen the submarine. This then drives the L/D further away from the optimum. The combined effect of diameter and length minimization as a means to obtain the least possible cost position has resulted in submarine designs with suboptimal hydrodynamic characteristics.

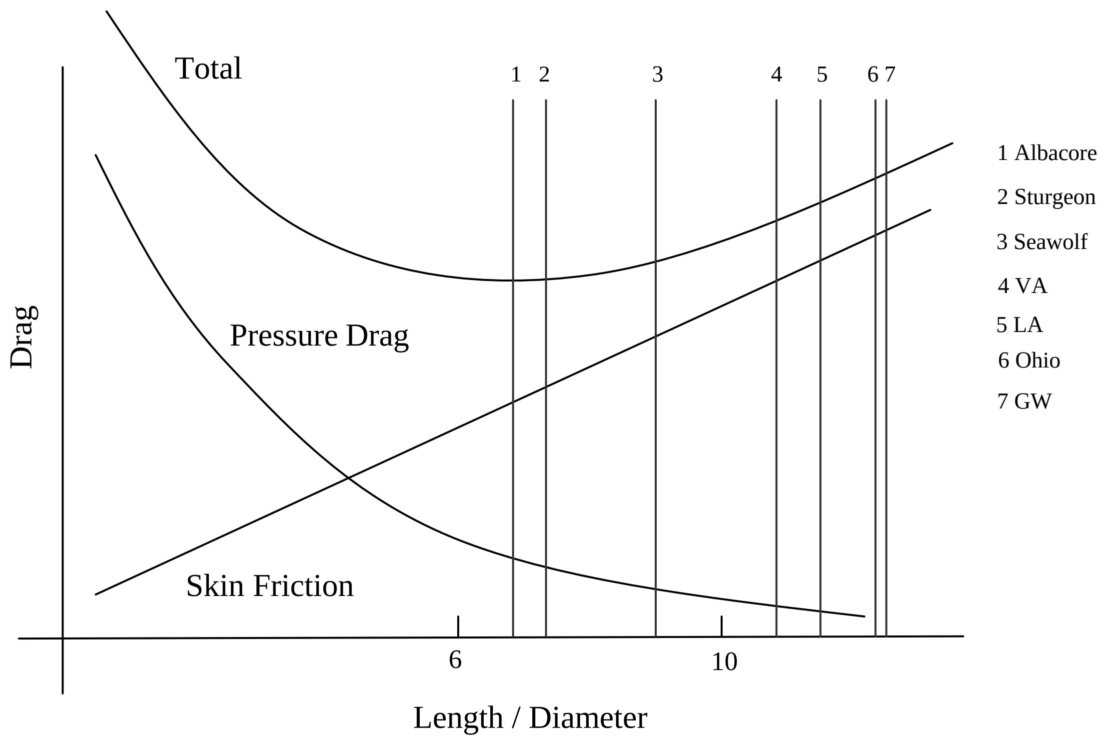


Figure 5. Total Hydrodynamic Drag versus the Ratio of Submarine Length and Diameter (After: Joubert, 2006)

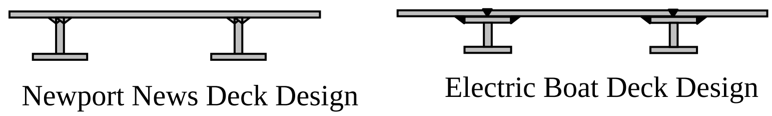
i. Mass Dispersion

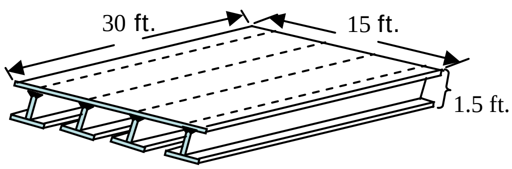
The previous examples reveal that weight-optimized designs do not necessarily minimize costs. To illustrate this point further, consider the analysis conducted at Quonset Point Shipyard circa 1987 when the shipyard was involved in the production of both the Los Angeles Class and Ohio Class submarines simultaneously.

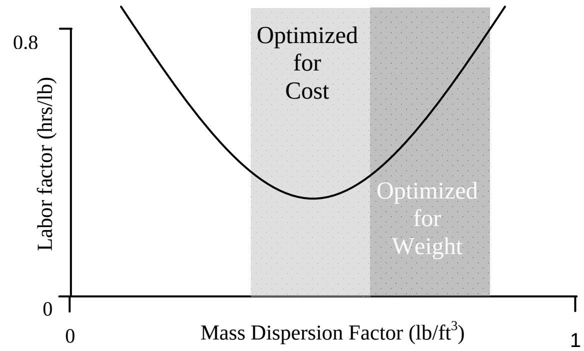
Todd Sedler (2007, November 8), an Engineer for NGSB, was asked to investigate why NGSB's labor estimations tracked so poorly as part of the Los Angeles Class modular construction program and to recommend a solution. He was also asked to determine which deck design methodology was more cost effective to build. NGSB

traditionally designed its decks as a T-on-plate, while GD/EB traditionally designed its decks as a plate-on-I-beam. The load-bearing capacity and shock requirements were identical for both designs. The T-on-plate was used for the Los Angeles Class, and the plate-on-I-beam was for the Ohio Class, both of which were under construction at Quonset Point at the time.

To investigate, Sedler observed the workers as they built various Ohio and Los Angeles decks around the facility. It was quickly apparent that labor was being driven in large part by the ease of accessibility for welding. This observation also held for tanks and bulkheads. Accessibility was a missing component in the company's labor-estimation procedure. The question became how important was accessibility, and how could it be quantified. He came up with what he called the *mass dispersion factor*. This simple parameter is closely related to the physical parameter of density. The *mass dispersion factor* is calculated by dividing the gross volume (cubic feet) occupied by the deck into the total weight (pounds) of the deck; this yields a pound per cubic foot (lb/ft^3) parameter that reflects how tightly packed or dispersed the mass in the deck is. Figure 6 illustrates a mass dispersion calculation (Sedler, 2007, November 8).







Example Problem:

$$Deck\ Weight = plate + tee + chocks + \ foundation\ backup\ structure = 6000 lbs$$
$$Deck\ Volume = lengh \cdot width \cdot depth = 30\,ft \cdot 15\,ft \cdot 1.5\,ft = 675\,ft^3$$
$$Mass\ Dispersion\ Factor = 6000 lbs / 675\,ft^3 = 8.88 lbs /\ ft^3$$
$$Labor = cutting\ labor + \ fitting\ labor + welding\ labor = 1200\ manhours$$
$$Labor\ \ factor = 1200\ manhours / 6000 lbs = 0.2 manhours / lb$$

Figure 6. Mass Dispersion Example Calculation and Results (After: Sedler, 2007, November 8)

Sedler calculated a mass dispersion factor for every forward-end and machinery compartment deck being built for the Ohio and Los Angles Classes. He then used the actual labor recorded for each deck and divided the labor by the weight of the deck to obtain a man-hour per pound of deck weight value. He could now plot the mass dispersion factor against the man-hours per pound.

Anecdotal evidence suggests that weight-optimized structures are very labor intensive. There are explanations for this. First, welding access is poor because weight-optimized designs typically consist of a lot of small, closely fit pieces. Second, weight-optimized structures tend to use thinner material—which distorts more easily during the welding process and, thus, requires more re-work, such as flame straightening.

The resulting curve shows that machinery decks that tend to use large, deep and widely separated frames result in a low mass dispersion factor (large volume for given weight). On the other hand, forward-end decks—which are relatively small, closely packed frames—result in a high mass dispersion factor (small volume for a given weight). Ultimately, what becomes apparent is a range of mass dispersion that minimizes cost, which does not correspond to the mass dispersion of weight-optimized designs. It is a primary objective of this research to determine if such a phenomenon can be demonstrated for submarine designs as a whole.

j. Summary

The primary difficulty with arguing that size or weight, whether increased or decreased, will result in predictable cost behavior is that size and weight alone do not capture the interaction between a vessel's structure and its installed systems and equipment. Unanticipated consequences may result if a decision is made to unilaterally reduce the size of a ship or submarine design without adjusting the quantity of internal systems and installed equipment. Designing these systems to perform similarly in the smaller space may lead to increases in complexity and the need for specialized parts, materials and construction methods; this, in turn, could drive up design hours, production hours and material costs. Design changes, maintenance and repairs may become more difficult and costly due to increased interference issues and reduced accessibility. Before long, the cost savings sought by reducing structural weight of the vessel may be more than offset by cost increases elsewhere. It seems density—a parameter that speaks to both the size of a vessel and the utilization of the internal spaces—may be a better predictor of design, procurement and even total life cycle costs.

C. DENSITY AS A COST DRIVER

The implications of breaking the long-standing tradition of treating weight as an independent variable and treating cost per unit weight as fixed or growing at a constant rate are potentially significant. The following are potential benefits of incorporating density effects into future cost estimates and design decisions.

The incorporation of density effects could:

1. Contribute to conversations about the correct mix of capability and flexibility in a design by allowing informed decisions regarding the space required and the cost to incorporate design flexibility, modularity, maintainability, reliability and life cycle cost-efficiency into future submarine designs.
2. Highlight the importance of a deliberate and carefully guarded acquisition strategy, and provide a means to reconcile seemingly contradictory strategic design goals.
3. Expose both the need and the means to compare naval ship and submarine designs of various types, sizes and levels of complexity.

1. Capability vs. Flexibility

An investment in design flexibility is warranted when the costs of change and uncertainty about the future are high. Figure 7 illustrates this relationship. Unfortunately, increased flexibility often comes at the expense of current capability. Figure 8 shows an efficient frontier of capability and flexibility. According to the curve, a full investment in current capability implies that the resulting design would be wholly inflexible. At the opposite extreme, a completely flexible vessel lacks any current capability. The area bound by the curve represents the feasible region; the area under this region indicates the amount of resources available to invest. A family of indifference curves exist with shapes governed by the environment in which the specific submarine design will operate. The right mix of capability and flexibility is found at the point where the marginal cost in foregone capability equals the marginal gain in flexibility. This is indicated at the point where the indifference curve is tangent to the efficient frontier. If technology is changing slowly, and if the tactical environment is relatively stable, capability should be favored over flexibility. This is represented on the efficient frontier by a relatively flat indifference curve, tangent at point *x* in Figure 8. However, if technology is changing rapidly or if the tactical landscape is uncertain, the investment mix should shift toward flexibility and away from current capability. The indifference curve rotates clockwise in response to this change in environment—causing a change in the proper mix of capability and flexibility, shown in Figure 8 as point *x'*.

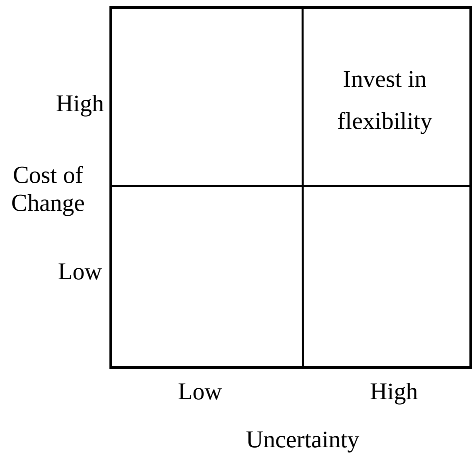


Figure 7. When to Invest in Flexibility

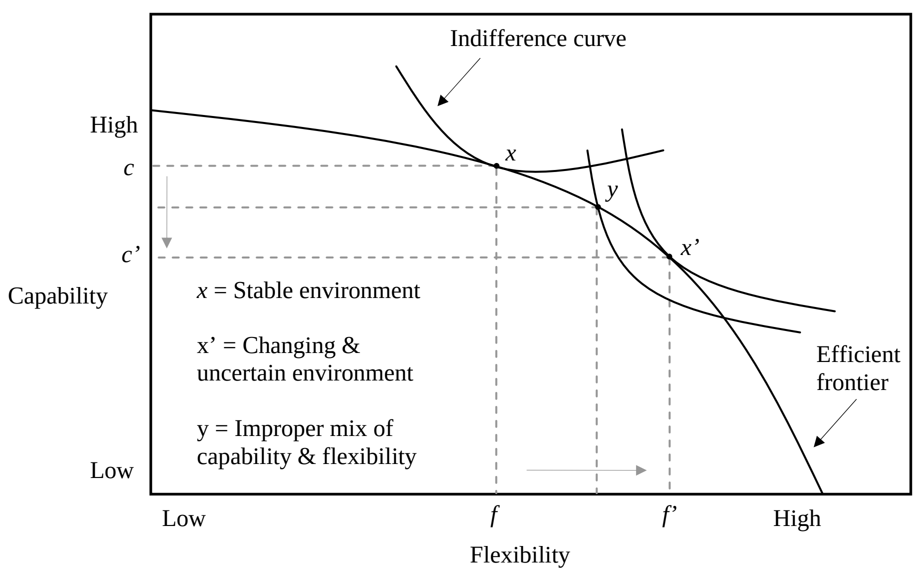


Figure 8. Capability and Flexibility Efficient Frontier

In a fiscally constrained environment, decision-makers have a tendency to become shortsighted when seeking cost efficiencies. Design characteristics that minimize procurement costs are likely to be implemented—even if there is a negative

impact on costs to be incurred in later phases of the life cycle. Current capability may be valued over future flexibility, and investment in the latter may be reduced. This is indicated on Figure 8 as point *y*. The danger in allowing such policies to go unchecked is that increased operating costs and prematurely irrelevant designs will constrain fiscal resources even further and will shorten the time between major design efforts.

Flexible submarine designs are larger than designs optimized for current capability. Increasing the size of a submarine design to incorporate flexibility may not be justifiable if the perceived cost is artificially inflated due to misconceptions about relationships between cost and weight. However, investments in flexibility may become justifiable if cost-estimators can show that the costs incurred by designing and building a larger submarine are less than weight-based cost-estimating relationships would suggest. Density reduction would then become a low-hanging fruit capable of granting additional design flexibility with minimal reductions in current capability—all at a lower cost than current wisdom would suggest.

2. Acquisition Strategy

Michael Porter, a professor at the Harvard Business School and leading authority on competitive strategy, created a system of categorizing business strategies into three broad segments. They are *cost leadership*, *differentiation*, and *focus* (also called *market segmentation*). Figure 9 shows the strategies mapped on a matrix of market scope and product type. A *focus* strategy is narrow in scope, while *cost leadership* and *differentiation* are relatively broad in market scope. The goal of a *cost leadership* strategy is to offer relatively standard products, but to produce them at such a low cost that the products can be offered at a price below that of the competition. A *differentiation* strategy seeks to create a specialized product that is particularly valued by the customer—such that the associated cost structure can be higher, but the customer is willing to pay a premium for the differentiated product to more than compensate for the higher cost structure. The *focus* strategy focuses on a narrow customer base and produces a customized product that meets the specific needs of the narrowly targeted customer (Porter, 1980).

Porter emphasizes that these strategies tend to be mutually exclusive; only one strategy can be successfully employed at a given time. To adopt a strategy that is neither fully *cost leadership* nor fully *differentiation* would create a situation referred to as being "stuck in the middle." A symptom of this condition is an organization that has lost its focus such that a clear vision about where the organization is headed cannot be established. This argument is based on the idea that a *differentiation* strategy requires a cost structure that is incompatible with the *cost leadership* strategy. Similarly, the standard products of a *cost leadership* strategy contain no differentiation. Therefore, *cost leadership* and *differentiation strategies* are incompatible (Porter, 1980).

Throughout the previous century, the Navy has adjusted its submarine acquisition strategy in response to advancements in technology and changes in the threat environment. Figure 9 shows the Submarine Force's strategic position over time.

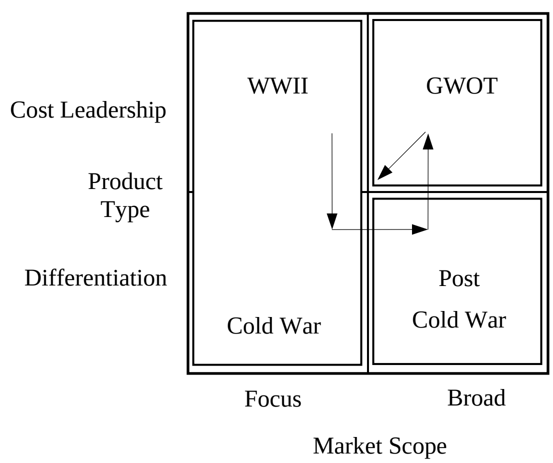


Figure 9. Changing Strategic Position of the U.S. Submarine Force over Time

The Submarine Force marketed early submarine designs using a *focused cost leadership strategy*. Indeed, submarines were the low-cost solution for anti-merchant and anti-warship tactics during WWI and WWII.

The advent of nuclear power redefined the realm of possibilities for submarines. The decision by the United States to focus on nuclear power and its associated

advantages meant shifting its strategy from one of *focused cost leadership* to one of *focused differentiation*. Indefinite patrol capability, no refueling, submerged transit and operations, and the safety features and quality control required to operate a nuclear reactor did not come cheap, but it was a service that the Navy sold successfully and a service that Congress was willing to pay for. The submarines that entered the Cold War were much bigger, faster and more capable than the workhorses of previous conflicts, yet their mission still remained fairly one-dimensional. Thus, the strategic position for the Submarine Force during the Cold War had shifted to one of *focused differentiation*.

The end of the Cold War marked the beginning of an interesting era for submarines. Without a symmetric threat, the Navy was compelled to justify submarines' continued relevance based on their potential versatility. With a submarine fleet optimized for Cold War conflicts, the Navy began exploring the services submarines could provide in other arenas. This pushed submarines from satisfying a focused mission to providing a broad range of services. The resulting strategic position during the post Cold War era was one of *broad differentiation*.

In the time since, the Navy has experienced growing pressure to trim costs wherever possible due to increased internal and external pressures on the defense budget. The Navy has responded by returning to the tenets of a *cost leadership* strategy in the area of ship, aircraft and submarine acquisition while continuing to serve the broad capability set expected by its customers. This has pushed the Submarine Force toward a *broad cost leadership* strategic position.

Unfortunately, the *broad cost leadership* strategic stance the Navy is seeking may be unattainable due to a continued desire for the differentiated capabilities current submarines provide. Figure 9 shows that the Navy may find itself "stuck in the middle" seeking an unachievable goal if a deliberate stance is not taken one way or the other. This is based on the tendency for acquirers to exploit product and process improvements to increase capability and reduce cost simultaneously. In fact, each product or process improvement can typically be exploited in only one of the following ways:

1. Increase the amount of capability in the same volume,

2. Reduce the volume required to offer the same capability, *or*

3. Provide same capability in the same volume at a lower cost.

A strategic contradiction occurs when ship and submarine designs are built smaller as a means to lower costs, while installed capability is maximized for the same reason. The smaller space requires increased innovation to incorporate the same capabilities. If increased capability per hull is desired, a larger—not smaller—design must be incorporated as to avoid the penalties associated with unnecessarily complex and congested designs.

3. Compensated Gross Tonnage

The practice of comparing commercial ships and commercial shipyards using weight measurements was standard practice in the commercial shipbuilding industry until the late 1960s. As ship designs became more complex and as shipyards began to adopt more modern shipbuilding techniques, raw weight measurements became increasingly incapable of capturing the amount of shipyard workload required to complete tasks. Without a common measurement of shipyard activity, measurements of relative shipyard efficiency were not possible.

In 1966 and 1967, the Community of European Shipyards Associations (CESA) and the Shipbuilders' Association of Japan (SAJ) met to develop a better measure of shipyard activity (OECD, 2007). They were motivated by a need to provide more accurate comparisons of the efficiency of shipyards producing ships of various types, sizes and levels of complexity. The compensated gross ton (*cgt*) concept was developed and formally introduced in 1968. "The *cgt*-system is a statistical tool developed in order to enable a more accurate macro-economic evaluation of shipbuilding workload than is possible on a pure deadweight tons (*dwt*) or gross tons (*gt*) basis" (OECD, 2007, p. 4).

In 1970, the Organization for Economic Co-operation and Development (OECD) adopted and promulgated a joint system for calculating the compensated gross ton (*cgt*). The concept underwent a number of revisions, with significant updates introduced in 1984, 1994 and most recently in 2007. The current *cgt* system was jointly developed by

the CESA, the SAJ and the Korean Shipbuilders Association (KSA), who together represent approximately 75% of world shipbuilding output (OECD, 2007).

The formula for compensated gross tonnage (*cgt*) is:

$$cgt = A \cdot (gt)^B$$

where,

$$\begin{aligned}
&cgt = compensated\ gross\ tonnage \\
&A = ship\ type\ factor \\
&gt = vessel\ gross\ tonnage \\
&B = ship\ size\ factor
\end{aligned}$$

The ship type factor, *A*, varies with ship complexity. The ship size factor, *B*, is actually defined as $B=b+1$, where *b* represents the diminishing influence of ship size on the work input required to build a single gross ton (OECD, 2007). Therefore, the compensated gross tonnage of a ship is a function of the size, weight and complexity of the ship design. The cost to build a ship depends on the contracted shipyard's efficiency in producing compensated gross tons. The *A* and *B* factors for various commercial ship types are shown in Table 1. Compensated gross tonnage factors do not yet exist for non-commercial naval vessels.

Table 1. *A* and *B* Factors for CGT Calculations (After: OCDE, 2007)

Ship Type	***A***	***B***
Car carriers	15	0.70
Full container	19	0.68
Ferries	20	0.71
Fishing vessels	24	0.71
General cargo ships	27	0.64
Reefers	27	0.68
Bulk carriers	29	0.61
Ro Ro vessels	32	0.63
LNG carriers	32	0.68
Combined carriers	33	0.62
NCCV	46	0.62
Oil tankers (double hull)	48	0.57
Passenger ships	49	0.67
LPG carriers	62	0.57
Chemical tankers	84	0.55

A plot of oil tanker compensated gross tons versus gross tons is provided in Figure 10 for illustrative purposes. Note that for oil tankers, gross tons and compensated gross tons are equal at 8,000 tons. This value corresponds to the gross tonnage of a small, general purpose oil tanker and represents the baseline ship for comparison purposes. Holding capability constant, compensated gross tonnage theory suggests oil tankers larger than the baseline should require less effort and should consistently cost less per gross ton to produce. This is represented by a compensated gross tonnage that is less than the gross tonnage of the vessel. Figure 10 shows that this is the case. Similarly, oil tankers smaller than the baseline require more effort per gross ton to achieve the same capability in a smaller vessel. This is represented by a compensated gross tonnage that is more than the gross tonnage of the vessel.

Oil Tanker Compensated Gross Tonnage (*cgt*) vs. Gross Tonnage (gt)

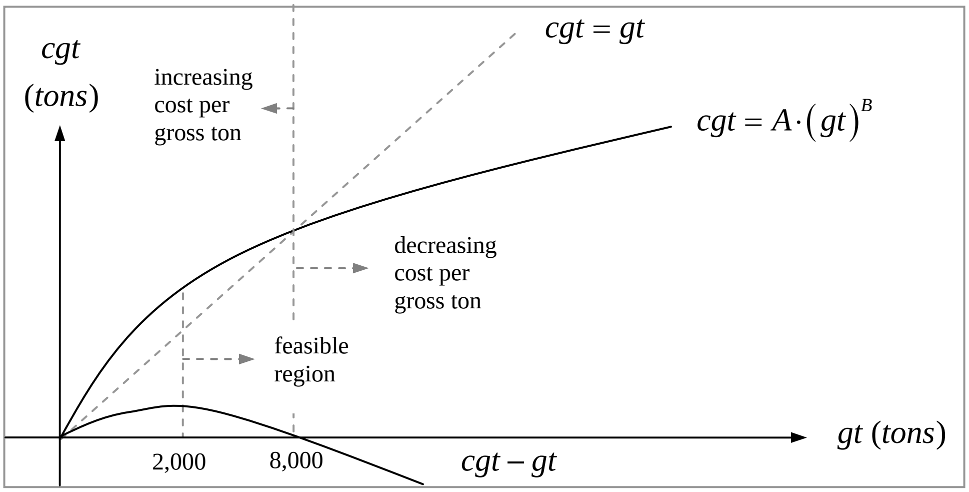


Figure 10. Oil Tanker Compensated Gross Tonnage vs. Gross Tonnage

In August 2005, First Marine International, Ltd., (FMI) reported the results of its Global Shipbuilding Industrial Base Benchmarking Study (GSIBBS) undertaken by the U.S. Office of the Deputy Under Secretary of Defense (Industrial Policy) (ODUSD(IP)) in 2004/2005. Compensated gross tonnage formed the basis for its shipyard productivity estimates (FMI, 2005). The objectives of the study were to:

- Compare the practices of U.S. and selected leading international commercial and naval/military shipbuilders in Europe and Asia.
- Identify specific changes to U.S. shipbuilding industry processes and to U.S. naval design and acquisition practices that will improve the performance of the shipbuilding enterprise. (FMI, 2005, p. 1)

Due to the nonexistence of *cgt* factors for military naval vessels and the shipyards' inability to provide data for their calculation, FMI estimated *cgt* factors for these vessel types. FMI used public-domain data and visual inspections of some of the naval vessels concerned to develop *cgt* estimates (FMI, 2005).

The overall performance of U.S. shipyards has been plotted in Figure 11 over the results of a 1992 study conducted by KPMG (UK) and FMI on the competitiveness of European Shipyards, together with results from subsequent studies. The range of possible values for U.S. shipyards reflects the uncertainty in the *cgt* calculations by FMI. The study found a correlation between shipyard performance (measured in man-hours per *cgt*) and the shipyards' adherence to a list of best practices (measured in overall best-practice rating).

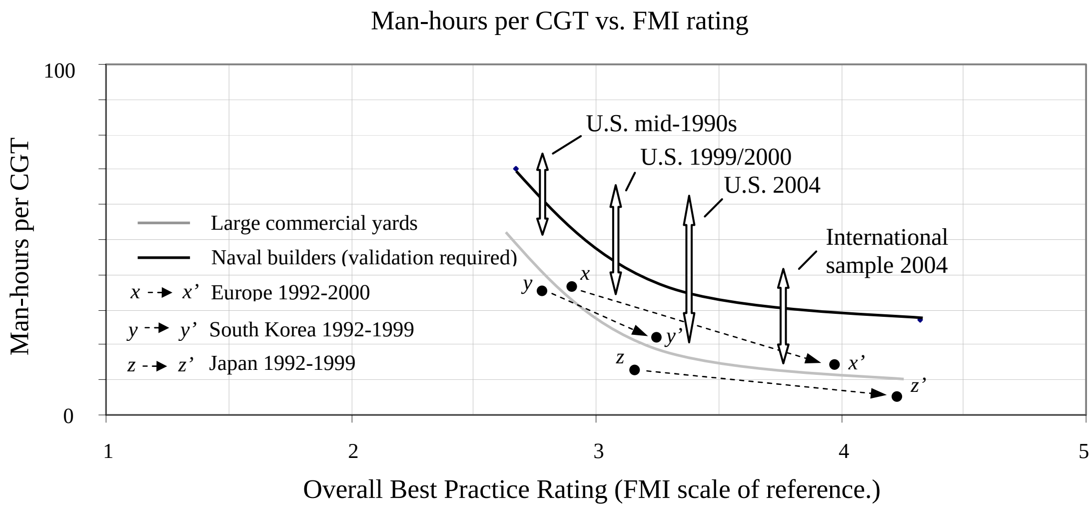


Figure 11. Man-hours per CGT versus FMI Rating (From: FMI, 2005)

The FMI analysis suggests that U.S. surface combatants have more work content per gross ton than the equivalent international vessel—leading to high *cgt* values. FMI observed that one major contributor to the high work content of U.S. naval vessels is the increased levels of management, technical and administrative resources required to execute the design and procurement effort. Other sources of increased work content arise due to advances in technology, the addition of more capability to fewer vessels and compromises between the Navy and Congress. All these combine to contribute to trends

of increasing complexity. Increased complexity reduces shipyard productivity in the form of a first-of-class performance drop-off phenomenon and sustained lower performance.

The principle driver of complexity and, hence, work content identified by FMI, is design specification. FMI estimates that a U.S. destroyer (DDG) contains 50% more work content than a comparable modern international destroyer. FMI also contends that part of the difference is capability related, but a significant portion is due to the density and general complexity of the vessel (FMI, 2005). The study stresses that an incremental increase in the complexity of an already complex vessel results in a disproportionate increase in work content. Said another way, increasing the quantity of installed systems or equipment in a vessel without adjusting the size of the vessel—or making a vessel smaller without adjusting the quantity of installed systems and equipment—will lead to cost increases greater than can likely be justified by the associated marginal increase in capability or performance.

In short, FMI warns that:

> Cost, risk, first-of-class performance drop-off and the probability of cost and schedule overrun, all increase with vessel complexity. Therefore, if exposure to all of the above is to be minimized, overly complex vessels should be avoided. The current trend for complex vessels may not be giving the best balance between capability and value for the money. (FMI, 2005, p. 15).

III. METHODOLOGY

A. GENERAL APPROACH

The following procedure was developed and executed in order to derive and test alternative measures of complexity for several submarine classes and to investigate their relationship to cost:

1. Develop a theoretical basis for density as a cost-driver
    a. Interviews with Engineers, Naval Architects, Cost Estimators, Acquisition Professionals, Program Managers
    b. Literature review
2. Select submarines for analysis
3. Collect data
    a. Gather cost data
        i. Normalize cost data
        ii. Create relevant cost segments
    b. Gather hours data
        i. Design hours
        ii. Production hours
    c. Gather design data
        i. Weights
        ii. Volumes
        iii. Permeability values
4. Calculate measures of density
5. Regress cost/hours vs. measures of density
6. Identify trends
7. Provide observations and recommendations for future analysis

B. SUBMARINES SELECTED FOR ANALYSIS

Each submarine design contains a mix of incremental and revolutionary design changes relative to its predecessor. In fact, the decision to procure a new class of submarines is only justifiable to the extent it is seen as the best means to exploit new technologies and/or confront emerging threats in a way that the current submarine classes or some non-material alternative are unable. In selecting the submarines to be used for analysis, a careful balance between maximizing the number of submarine classes considered and excluding non-analogous submarine designs from the data set was the primary objective. Data maximization is crucial, since for each of the regressions performed, a particular submarine class would provide but one datum point. The exclusion of non-analogous submarine designs is needed to minimize opportunities to draw conclusions from observed trends that may lack a sound theoretical basis for comparison. This reality is a significant contributing factor to the difficulty in identifying modern submarine cost-drivers.

The submarines selected for this study consist of the six most recent nuclear submarine classes acquired by the U.S. Navy. This group includes two ballistic missile submarine classes and four fast-attack submarine classes. The ballistic missile submarines are of the USS George Washington (SSBN 598) and the USS Ohio (SSBN 726) Classes. The fast-attack submarines are of the USS Sturgeon (SSN 637), USS Los Angeles (SSN 688), USS Seawolf (SSN 21) and USS Virginia (SSN 774) Classes. Where deemed relevant, the USS Los Angeles (SSN 688) Class was subdivided into two of its major design evolutions: the “Classic” Los Angeles Class, starting with SSN-688, and the “Improved” Los Angeles Class, starting with SSN-751.

Below are the characteristics of the submarine classes selected for analysis:

USS George Washington (SSBN 598) Class

Surface Displacement:	7331 Long Tons (LT)
Submerged Displacement:	8248 LT
Length:	425 ft
Diameter:	33 ft
Years Commissioned:	1959-1961

USS Sturgeon (SSN 637) Class

Surface Displacement:	4256 LT
Submerged Displacement:	4779 LT
Length:	292 ft
Diameter:	32 ft
Years Commissioned:	1967-1975

USS Ohio (SSBN 726) Class

Surface Displacement:	16730 LT
Submerged Displacement:	18748 LT
Length:	560 ft
Diameter:	42 ft
Years Commissioned:	1981-1997

USS Los Angeles (SSN 688) Class

Surface Displacement:	6086 LT
Submerged Displacement:	6929 LT
Length:	360 ft
Diameter:	33 ft
Years Commissioned:	1976-1985

USS Los Angeles (SSN 688) "Improved" Class

Surface Displacement:	6127 LT
Submerged Displacement:	6859 LT
Length:	360 ft
Diameter:	33 ft
Years Commissioned:	1988-1997

USS Seawolf (SSN 21) Class

Surface Displacement:	8097 LT
Submerged Displacement:	9137 LT
Length:	353 ft
Diameter:	40 ft
Years Commissioned:	1997-2005

USS Virginia (SSN 774) Class

Surface Displacement:	6980 LT
Submerged Displacement:	7841 LT
Length:	377 ft
Diameter:	34 ft
Years Commissioned:	2004-present

C. DATA

1. Cost Data

Cost data used for analysis were retrieved from the "Historical Cost of Ships" database program maintained by NAVSEA 05U. According to the 2005 NAVSEA *Cost Estimating Handbook*, the "Historical Cost of Ships" database contains initial acquisition/major conversion costs and technical data for Navy ships and craft from 1900 to the present. For ships built after 1952, it also contains SCN end-cost data broken-out by P-5 budget category. An example of a P-5 budget report is provided in Appendix B.

The database provides a central data source containing budget and actual cost data on delivered ships and craft and is used to respond to questions from higher echelon Navy/DoD on cost of historical ships (Deegan, 2005).

NAVSEA 05U provided SCN end-cost data broken-out by P-5 budget category, organized according to class and hull number for the lead and follow-on submarines in each submarine class selected for analysis. The major categories of the P-5 Exhibit applicable to submarines are:

- **Basic Construction—**includes all allowable shipbuilder direct labor, indirect labor (overhead), and material costs required to construct the ship, plus an amount for shipbuilder cost of money and profit.

- **Construction Plans—**includes the nonrecurring costs related to detailed construction plans and other associated engineering tasks for lead ships. Planning yard, lead yard, and follow yard costs for ship classes may also be accounted for in this category or in the Basic Construction category.

- **Change Orders—**consists of dollars required to fund necessary changes after the shipbuilding contract is awarded.

- **Electronics—**includes production components, training support equipment, sonars, towed arrays, combat systems, external communications, satellite navigation and communication equipment, integrated command and control (C2) communication equipment, integrated C2 systems, computers and displays, test and engineering services, and repair parts associated with installation.

- **HM&E (Hull, Mechanical & Electrical)—**includes items such as interior communications, inertial navigation systems, deep submergence systems, periscopes, small boats, inflatable life boats, special vehicles, environmental protection equipment, training support equipment, repair parts associated with installation of HM&E equipment, propulsion equipment (non-nuclear), electric generator and motor equipment, and all medical equipment provided by the Bureau of Medicine and Surgery (BUMED).

- **Propulsion—**includes turbines, gears, and nuclear propulsion reactors and associated equipment.
- **Other Cost—**provides a convenient catch-all of miscellaneous but important categories of an end-cost estimate, including Test and Instrumentation (T&I), Stock Shore-based Spares and Other Support.
- **Ordnance—**includes fire and missile control systems, search radars, missile launching systems, gun systems, training support equipment, test and integration services and other ordnance equipment.
- **Escalation—**the cost to be paid to the shipbuilder for the effects of inflation over the long ship construction period.

The summation of these categories is referred to as the ship End-cost and represents the total cost of constructing and integrating the ship and shipboard components (NAVSEA 05U, 2005).

a. Cost Data Normalization

The SCN End-cost data broken-out by P-5 budget category contained within the the "Historical Cost of Ships" database program are recorded in Then-year (TY) dollars according to either the Labor Midpoint (*LM*) or the Material Midpoint (*MM*), which are unique for each submarine hull (NAVSEA 05U, 2005). According to the Naval Center for Cost Analysis (NCCA), TY dollars are synonymous with Budget (BY) dollars, which are funds inflated for budgeting purposes that include inflation for the years of expenditure, calculated using the outlay profile of the relevant acquisition category. *LM* and *MM* are defined as follows:

$$Labor\ Midpoint\ (LM) = S/C + 0.56 \cdot (DEL - S/C)$$

$$Material\ Midpoint\ (MM) = AWD + 0.44 \cdot \left[(DEL - 3) - AWD\right]$$

where,

$$AWD = Contract\ Award\ Date$$
$$DEL = Ship's\ Delivery\ Date$$
$$S/C = Start\ of\ Construction\ Date$$

To enable meaningful cost comparisons among submarines and submarine classes, the cost data were normalized to a common Constant Year (CY), where CY refers to a categorization of funds from which the effects of inflation have been removed. Therefore it is possible to compare purchasing power or funding between years (NAVSEA 05U, 2005). All cost data used for this research, unless otherwise noted, have been normalized to CY 2007 dollars using SCN-specific inflation indices provided by the Naval Center for Cost Analysis (NCCA).

b. Relevant Cost Categories

The various submarine density approximations developed for this study were regressed against submarine end-cost values and meaningful segments of submarine end-cost. The various P-5 budget category elements that make up an end-cost estimate can be grouped into three cost segments useful for trend analysis. The three cost segments, per *CEH*, are:

- Shipbuilder Costs,
- Government-furnished Equipment (GFE) and
- Other. (NAVSEA 05U, 2005).

Based on interviews and literature reviews, End-cost less Other, Shipbuilder Cost and Government-furnished Equipment (GFE) contain cost categories that may be density-driven and were thus investigated for a positive relationship.

The Shipbuilder Costs segment is the sum of the following categories for the P-5 budget report:

- Basic Construction,
- Change Orders, and
- Escalation.

Recall that Basic Construction includes all allowable shipbuilder direct labor, indirect labor (overhead), and material costs required to construct the ship, plus an amount for shipbuilder cost of money and profit; Change Orders includes those dollars required to fund necessary changes after the shipbuilding contract is awarded; and Escalation is the cost to be paid to the shipbuilder for the effects of inflation over the long ship construction period (NAVSEA 05U, 2005). Cost data that contributed to the Shipbuilder Costs element calculations were normalized using the Labor Midpoint as the base date.

The Government-furnished Equipment (GFE) segment is the sum of Electronics, HM&E, Propulsion and Ordinance categories of the P-5 budget report. Recall that Electronics includes production components, training support equipment, sonars, towed arrays, combat systems, external communications, satellite navigation and communication equipment, integrated command and control (C2) communication equipment, integrated C2 systems, computers and displays, test and engineering services, and repair parts associated with installation. HM&E includes items such as interior communications, inertial navigation systems, deep submergence systems, periscopes, small boats, inflatable life boats, special vehicles, environmental protection equipment, training support equipment, repair parts associated with the installation of HM&E equipment, propulsion equipment (non-nuclear), electric generator and motor equipment, and all medical equipment provided by BUMED. Propulsion includes turbines, gears, and nuclear propulsion reactors and associated equipment; and Ordinance includes fire- and missile-control systems, search radars, missile-launching systems, gun systems, training support equipment, test and integration services and other ordnance equipment (NAVSEA 05U, 2005). Cost data that contributed to the GFE element were normalized using the Material Midpoint as the base date.

As mentioned previously, the Other segment is a convenient catch-all of miscellaneous but important categories of an end-cost estimate—including Test and Instrumentation (T&I), Stock Shore-based Spares and Other Support. Although each ship will bear some T&I costs, the majority of the T&I costs for a class of ships are charged to the lead ship. These costs include government-responsible testing and instrumentation incident to routine or special trials leading to qualifying a ship for active service. The Stock Shore-based Spares funded in this category are back-up spares for stock ashore or aboard tender/repair ships. Stock spares funded by SCN are limited to first-of-its-kind installations on the lead ship. In other cases, shore-based spares are funded in the OPN or WPN Appropriation. Specific policy is outlined in *NAVSEA Instruction 4400.03A.* There are a number of programmatic efforts funded by the PM with funds set aside in the Other Support category. Some of the efforts that are visible in most end-cost estimates are as follows:

- Planned Maintenance Subsystem (PMS): Installed aboard ship. Identifies the servicing and maintenance requirements of major ship systems or subsystems.
- SUPSHIPS Material or Services: The Navy has O&MN-funded SUPSHIPS offices at major private shipbuilding yards to provide on-site Navy management and contracting services. Specific tasks requested by PMs for SCN shipbuilding programs are funded in this category. In addition, other similar Navy-support Activities may be tasked and funded by the Other Support category.
- Contractor-support Services: Separately contracted for services required by the PM to fulfill program management responsibilities.
- Travel: Travel by Naval Activities (personnel) in direct support of shipbuilding. Excludes travel costs of NAVSEA Headquarters and those activities that are mission-funded—such as SUPSHIPS, which are funded with operating funds.
- Commissioning Ceremony: Costs directly related to the Commissioning Ceremony (over and above shipbuilder costs included in basic

construction) are funded in this category. These tasks and other similar tasks constitute the efforts in the Other Support category.

2. Hours Data

The man-hours required to perform the detailed design for each submarine class and then to produce the submarines within each class were used to determine how density may relate to producibility. NAVSEA 05C provided detailed design and production hours data for the Ohio, Los Angeles, Seawolf and Virginia Classes. For submarine classes prior to the Ohio Class, accurate man-hours data were not obtainable.

Based upon interviews with engineers and naval architects at NAVSEA 05U, as well as interviews with previous and current project managers, it became apparent that the method of detailed design hours data collection for the Ohio and Los Angeles Class submarine classes differed from the man-hours accounting practices employed during the Seawolf and Virginia Class procurement efforts. Many, perhaps as much as half of the hours required to complete the detailed design effort for the Ohio and Los Angeles Classes, were not specifically accounted for because at that time, a high percentage of detailed design was mission-funded. The portion of the detailed design effort that occurred within a mission-funded environment did not require the same hours accounting methods as does work performed by a government contractor. As submarine detailed design and procurement shifted toward private government contractors, the need for thorough and accurate hours data has increased; indeed, current accounting methods ensure hours data is sufficient and consistent for comparative study. The differences in hours accounting was considered when comparing the detailed design hours data for earlier submarines to the data for more recent designs.

An additional difference in the accounting for design hours and production labor hours was accounted for based on a peculiarity of the Virginia Class procurement effort. The detailed design contract for the first Virginia Class submarine (SSN 774) included non-recurring production man-hours referred to as “Design to Innovation” (D-I). D-I consists of construction tasks that are budgeted and performed during the execution of the detail design contract (NAVSEA 05U, 2005). D-I hours were subtracted from the total

detailed design hours and added to the SSN-774 production hours to make Virginia Class detailed design hours analogous to those of the Seawolf Class, and to make Virginia Class production hours analogous to the other three classes of submarine for which production hours data were available.

3. Design Data

Submarine design data were provided by NAVSEA 05U, NGSB and GD/EB. Additional design data were retrieved from documentation available via open sources. Design data were used to derive density measurements for submarines. These measurements act as a proxy for how tightly systems and equipment are placed within the submarine hull.

a. Weights

Weight management and accounting are critical to successful submarine design. Given the importance of achieving a specific end-weight for a given volume and the importance of ensuring a dynamically stable design, the weight data maintained for various submarines designs is all-inclusive and highly accurate. Weight data provided by NAVSEA 05U were broken down according to standard Ship Work Breakdown Structure (WBS) groups. The weights of Lead Ballast, Variable Ballast and Main Ballast were also provided. Table 2 provides a summary of the submarine weight breakdown provided by NAVSEA 05U.

Table 2. Standard Submarine Weight Groups

Group 100	Hull Structure
Group 200	Propulsion Machinery
Group 300	Electric Plant
Group 400	Command and Surveillance
Group 500	Auxiliaries
Group 600	Outfit and Furnishings
Group 700	Weapons Systems
net Σ :	***Condition A-1***
	Displacement Correction Lead
	Stability or Trim Lead
	Margin Lead
net Σ :	***Condition A***
	Fixed and Variable Loads
	Variable Ballast
	Residual Water
net Σ :	***Condition N Surfaced***
	Net Main Ballast Tanks
Total Σ:	***Condition N Submerged***

b. Volumes

Volume data were provided by NAVSEA 05U. Volume data were provided in cubic feet and were broken down by major compartment—the sum of which represents the internal submarine pressure hull volume.

c. Permeability

Permeability data were provided by GD/EB and by NAVSEA 05U. The data were broken down by major compartment. NAVSEA 05U provided Permeability values broken down by major compartment and the overall Permeability percentage for each submarine Class under consideration.

D. DENSITY CALCULATIONS

The overall weight density of each submarine (when submerged) is an insufficient proxy for density for use in this research because Archimedes' Principle requires the densities of all submarines (when submerged) to achieve densities equal to that of water. The primary goal of each density calculation derived was to arrive at the best means to represent how compactly the systems and installed equipment have been placed within each submarine design. The derived density measurements were evaluated against their perceived theoretical relevance based on reviews of literature pertaining to submarine design and interviews with naval architects, engineers, cost estimators, program managers and acquisition professionals. Of all the methods considered, Arc-permeability and Internal Density possess defendable theoretical bases for use as proxies for design complexity. These terms are defined and developed below.

1. Internal Density

The general philosophy of modern U.S. Naval submarine design has been to utilize single-hull construction and to minimize the types and quantity of equipment mounted external to the pressure hull. Additionally, the items mounted external to the pressure hull tend to be of similar type and quantity (Secondary Propulsion Motor (SPM), anchor and anchor chain, towed arrays, etc.). For these reasons, the derivation of an internal submarine density was deemed an appropriate means to compare U.S. submarine designs. Some exceptions to this general principle exist that have caused the six submarines being considered to fall into one of three categories. First, the George Washington and Ohio classes are ballistic missile submarines and contain a large missile compartment amidship that the fast-attack submarines lack. Second, the Sturgeon and

early Los Angeles Classes are fast-attack submarines but lack the Vertical Launch Sytem (VLS) and Wide Aperture Arrays (WAA) common to the Seawolf, Virginia and later Los Angeles Classes. Third, in addition to some external components, the Seawolf and Virginia Classes represent a transition toward increasingly modular construction. This study considered this natural grouping when evaluating the observed cost vs. Internal Density relationships. It should be noted that while a comparison of internal densities may be appropriate for the available submarine data set under consideration, such comparison may not be appropriate for data that includes a mix of single- and double-hulled submarines, submarines designed according to different design philosophies, or submarines utilizing various propulsion methods.

Internal Density is defined as follows:

$$Internal\ Density = \frac{weight\ of\ interior\ systems\ \&\ equipment}{volume\ of\ submarine\ interior}$$

The numerator of the Internal Density calculation should include the weight of items that contribute to the consumption of available interior volume of the submarine hull. The denominator is the interior molded volume of the pressure hull. The weight of interior systems and equipment was approximated as the *Condition A-1* weight less Group 100 (Hull Structure), which is the sum of Groups 200 through 700 weights.

The approximation for Internal Density becomes:

$$Internal\ Density \approx \frac{Group\ 200\ thru\ 700\ weights}{volume\ of\ pressure\ hull}$$

An alternate means of expressing the Internal Density values for each submarine is in terms of Internal Specific Gravity. Specific Gravity is defined as the ratio of the density of a given substance to the density of water.

Therefore, the alternate expression for Internal Density then is:

$$Internal\ Specific\ Gravity \approx \frac{Internal\ Density}{Density\ of\ H_2O\ @\ 70°F}$$

2. Arc-permeability

A principal goal of this research has been to discover and exploit design parameters that have been accurately recorded and/or could be accurately calculated from recorded data, but have been overlooked by cost estimators, program managers, decision makers or appropriators to judge the cost effectiveness of a design. Indeed, a parameter suitable for revealing the cost of density would ideally be a parameter that has not been managed as an indirect means to manage cost. Once a design parameter has been identified as a cost-driver and adopted as an independent cost variable, further correlation between that parameter and cost should be treated as suspect due to its ability to become artificially derived.

A contractor aware of a parametric relationship in use may understand that cost concessions are accepted with less resistance prior to reaching the expected cost per parameter target, while any justifications for cost growth above said target are likely to receive additional scrutiny. This self-fulfilling prophesy effect can render a parametric cost relationship devoid of the theoretical basis on which the initial correlation was based.

Permeability is a design parameter that appears to have escaped the scrutiny of top-level policy- and decision-makers, yet contains the information necessary to investigate the relationship between density and cost. Permeability represents the volume percentage of a submarine compartment *not* occupied by items. It is essentially the ratio of the molded volume of the hull to the floodable volume. Permeability values are used in stability calculations to predict changes in trim during a flooding casualty if a compartment was breeched and the permeable space filled with water. A permeability of 60% would mean that 40% of the molded volume was occupied by equipment (components, piping, wiring, joinerwork, structure, etc.).

Permeability data were provided by GD/EB Shipbuilding in Groton, CT, for the following submarine classes and are based on calculations performed at GD/EB:

- USS Sturgeon (SSN 637)
- USS Ohio (SSBN 726)
- USS Seawolf (SSN 21)
- USS Virginia (SSN 774)

Permeability values were reported according to the following major compartments as applicable:

- Forward Compartment (FWD)
- Control
- Missile Compartment
- Reactor Compartment (Rx)
- Auxiliary Machinery Room (AMR)
- Engine Room (ER)

Design records maintained by Naval Sea Systems Command (NAVSEA) are another source of permeability data. Chapter 5 includes a recommendation that future efforts to quantify the density/cost relationship or develop compensated gross tonnage (*cgt*) factors for naval vessels include this and any additional sources of permeability data. The permeability data provided by GD/EB are sufficient to begin to reveal the suitability of using permeability data to underpin the effects of density on cost.

It is desirable that the parameter used as a proxy for density be directly proportional to density. However, permeability is inversely proportional to density. As density increases, permeability decreases. Arc-permeability is the term developed for this research to refer to the volume percentage of *items* within a molded volume and contains the desired attribute of varying proportionally with density. As density increases, arc-permeability increases.

Arc-permeability Factor definition:

$$ArcPermeability\ Factor\ (APF) = percentage\ of\ compartment\ occupied\ by\ items$$

Arc-permeability Factor calculation:

$$APF_{(compartment)} = 100\% - permeable\ volume\ percentage_{(compartment)}$$

A composite Arc-permeability Factor (APF) was calculated by calculating the weighted average APF for the combined Forward Compartment (FWD) and Engine Rooms (ER) in order to compare analogous portions of each submarine for which arc-permeability data were provided. The composite Arc-permeability Factor (APF) was calculated as follows:

$$APF_{(FWD+ER)} = APF_{(FWD)} \cdot \frac{Vol_{(FWD)}}{\left(Vol_{(FWD)} + Vol_{(ER)}\right)} + APF_{(ER)} \cdot \frac{Vol_{(ER)}}{\left(Vol_{(FWD)} + Vol_{(ER)}\right)}$$

where,

$$APF_{(FWD+ER)} = Combined\ FWD\ and\ ER\ APF$$
$$APF_{(FWD)} = FWD\ APF$$
$$APF_{(ER)} = ER\ APF$$
$$Vol_{(FWD)} = FWD\ Volume\ (cubic\ feet)$$
$$Vol_{(ER)} = ER\ Volume\ (cubic\ feet)$$

The combined FWD and ER APF excludes the Reactor Compartment (Rx) from all four submarines and the Missile Compartment from the Ohio Class thus enabling a comparison of analogous portions of each submarine class.

E. ANALYSIS

The following cost and hours segments were regressed against Internal Density and $APF_{(FWD+ER)}$:

- Shipbuilder Cost (CY07$) per Long Ton
- Government-furnished Equipment (GFE) (CY07$) per Long Ton
- End-cost less Other (CY07$) per Long Ton
- Detailed Design Hours per Long Ton
- Production Hours per Long Ton

Observations on the above results are included in Chapter IV.

Where data were available, values for the first and the fifth ship built at GD/EB are plotted. Submarines constructed at a common shipyard were used to control for differences among the various shipyards that have and currently build submarines.

The Virginia Class is being built under a teaming relationship between NGSB and GD/EB, where each shipyard constructs roughly one half of each submarine, and the shipyards take turns acting as the lead yard and performing the final fabrication. This causes an anomaly unique to Virginia Class data and is discussed in the results section. For the Virginia Class data, submarines where GD/EB acted as the lead shipyard (SSNs 774,776,778,780) are used to project values for the fifth GD/EB-led Virginia Class submarine (SSN 782).

Three Seawolf Class submarines were built prior to the cancellation of the Seawolf program. Additionally, the third in the Seawolf Class, the USS Jimmy Carter (SSN-23) was a longer version of the USS Seawolf (SSN 21) and USS Connecticut (SSN 22). For these reasons, fifth-ship data are a projection of cost data for SSN 21 and SSN 22.

IV. RESULTS

This section presents the results of investigating density as approximated by Internal Density and Arc-permeability versus the relevant cost and hours segments. It is evident from the data and supported by expert opinion that the submarine designs being considered fall into three natural groupings based on a combination of submarine type, capability (driven largely by level of acoustic quieting), and acquisition environment (production rate, vendor base, etc.). The natural groupings are as follows:

- Ballistic Missile Submarines (SSBNs)—George Washington (GW) and Ohio classes.
- Early Fast-attack Submarines (SSNs)—Sturgeon, Los Angeles (LA) and Improved Los Angeles (LA – I) Classes.
- Recent Fast-attack Submarines (SSNs)—Seawolf and Virginia Classes.

The data support the theories presented in Chapter II. As with the mass dispersion analysis performed by Sedler on the component level, there seems to be some range of density for which cost per unit weight is minimized. Also, current design philosophies appear to be forcing submarine designs away from the optimum. The concave curves drawn on the following charts are notional. They represent a family of such curves of the same shape that could be drawn higher or lower based on submarine type, capability level, and acquisition environment.

A. SHIPBUILDER COST

The first and fifth GD/EB ship *shipbuilder cost* per long ton (CY07$) versus *internal density* (pounds per cubic foot) are shown in Figure 12. The first and fifth GD/EB ship *Shipbuilder Cost* per long ton (CY07$) versus combined Ops Compartment & Engine Room *Arc-permeability* (percent) are shown in Figure 13. Of note is the fact that the first GD/EB “Improved” Los Angeles Class submarine (SSN 751) cost more than the first GD/EB Los Angeles Class submarine (SSN 690). This data does not correct for the fact that a large percentage of the “Improved” Los Angeles design was mature (up to

60%) and unchanged in SSN-751. Such a correction would increase the shipbuilder cost for the "Improved" Los Angeles Class and further underscore the point being made that the increased density of the "Improved" Los Angeles Class required additional shipbuilder effort per long ton to produce.

The first Virginia Class submarine cost less per long ton than the first Seawolf Class submarine. This is significant because the Virginia Class is the first fast-attack submarine design to break the trend of increasing shipbuilder costs per long ton with each subsequent design. It is also the first submarine to break a similar trend of increasing density with each subsequent design.

The simulated fifth GD/EB-led Virginia Class submarine actually incurred more shipbuilder cost than the first. This is caused by the significant re-design effort enacted to bring down submarine costs as a whole. Both the first and the simulated fifth Virginia Class submarines' costs are also inflated due to the multiple-contractor teaming effort employed to preserve the industrial base for designing and building submarines. Theoretical first and fifth Virginia Classes are shown in grey that have been corrected for the anomalies mentioned previously that are unique to the Virginia Class procurement effort.

There is a significant decrease between the shipbuilder costs per long ton for the first and simulated fifth Seawolf Class submarines. This is evidence of the "first-in-class performance drop-off" phenomenon that suggests excessively dense designs increase the complexity and cost risk of a design; these, then, increase the quantity and intesify the severity of problems encountered in the initial build effort. In short, they ultimately translate to increased first-ship costs.

The fifth George Washington and fifth Ohio Class submarines may be demonstrating that unnecessarily low densities may also cause one design to be more expensive to build than another. If so, this would lend credence to the mass dispersion theory and represent a practical example of the quote by Albert Einstein, "Everything should be made as simple as possible, but not simpler."

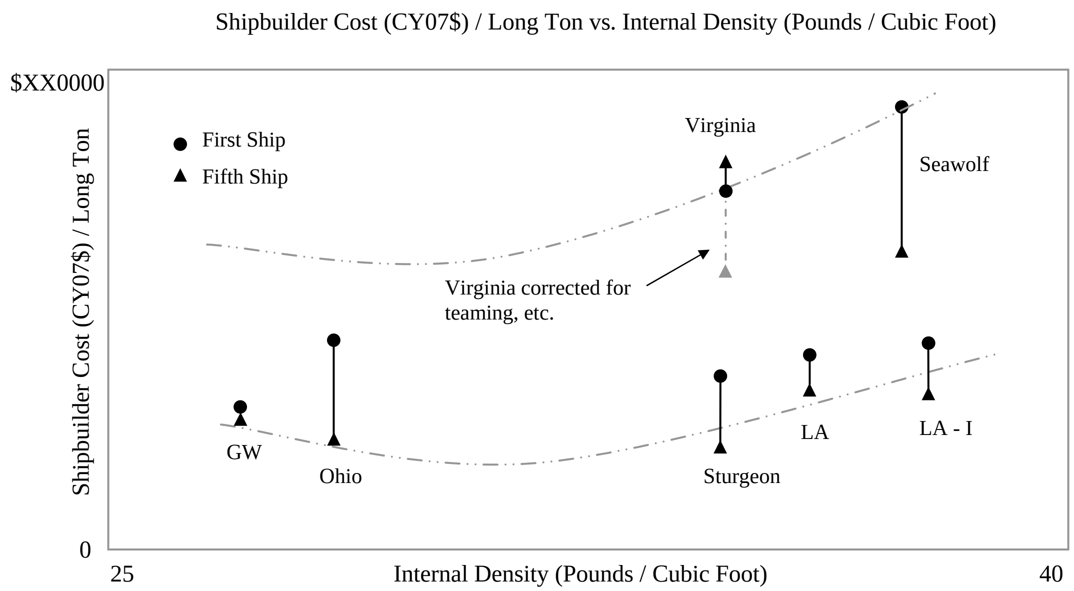


Figure 12. First and Fifth Ship Shipbuilder Cost per Long Ton (CY07$) versus Internal Density (pounds per cubic foot)

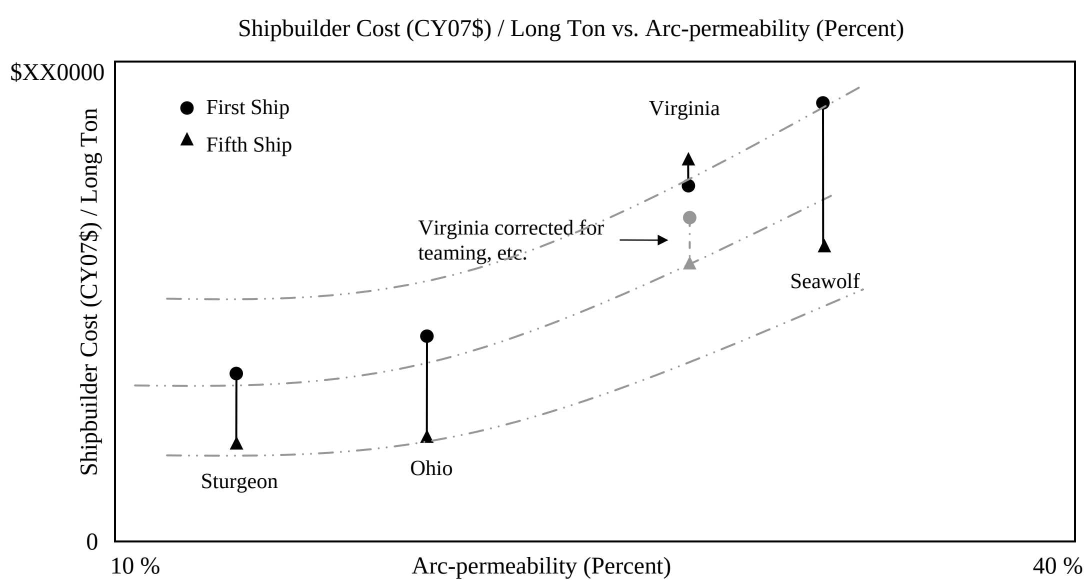


Figure 13. First and Fifth Ship Shipbuilder Cost per Long Ton (CY07$) versus Arc-permeability (percent)

B. GOVERNMENT-FURNISHED EQUIPMENT (GFE)

The first and fifth GD/EB ship *Government-furnished Equipment (GFE)* costs per long ton (CY07$) versus *Internal Density* (pounds per cubic foot) are shown in Figure 14. The first and fifth GD/EB ship *Government-furnished Equipment (GFE)* per long ton (CY07$) versus combined Ops Compartment & Engine Room *Arc-permeability* (percent) are shown in Figure 15. This investigation of GFE costs demonstrates that density not only affects the costs associated with building a submarine, but it also influences the cost of the parts and materials with which it is built.

The large reduction in GFE cost between the first and simulated fifth Virginia Class submarines is an example of the cost reductions possible when product and process improvements are directed toward lowering costs. Instead of using product and process improvements to improve the amount of capability in a given volume or to provide the same capability in a smaller space, such improvements have been directed toward offering the same capability in the same space for less cost. The goal to reduce the cost of a Virginia Class submarine to $2 billion (CY05$) has aligned the actions of those involved to produce a contributive, vice a canceling effect.

The GFE costs for the first George Washington Class, as shown in Figure 14, have been reduced by subtracting a large non-recurring ordinance investment that was assigned to the first submarine in the class.

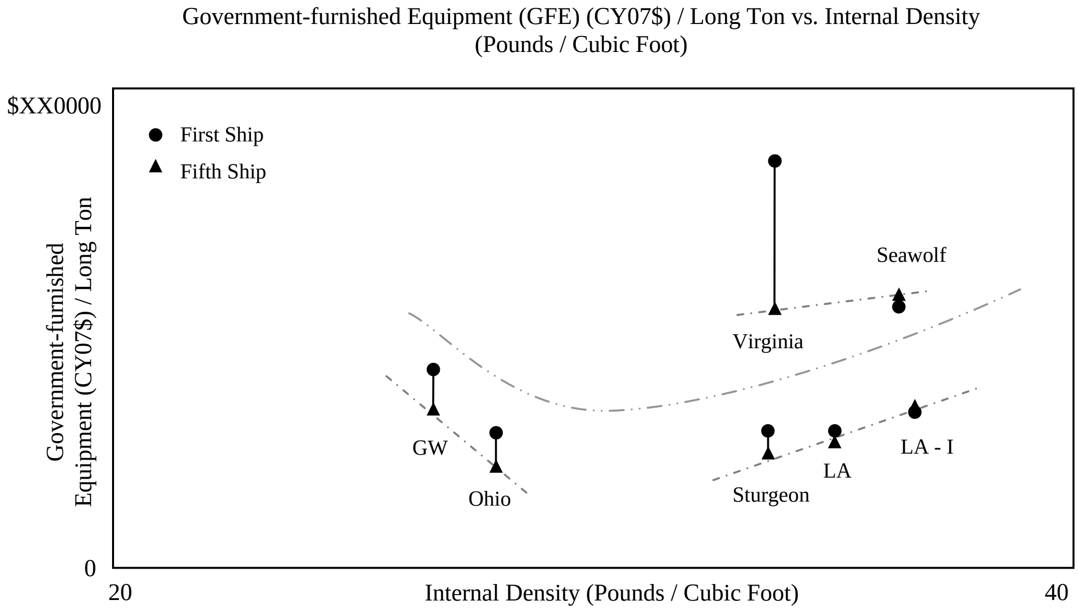


Figure 14. First and Fifth Ship Government-furnished Equipment (GFE) per Long Ton (CY07$) versus Internal Density (pounds per cubic foot)

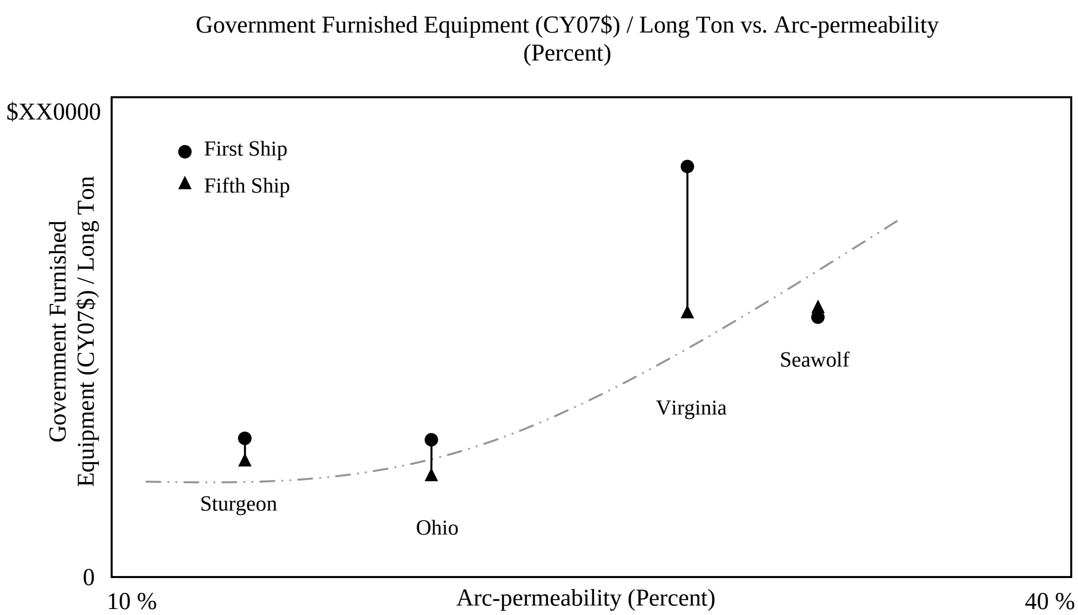


Figure 15. First and Fifth Ship Government-furnished Equipment (GFE) per Long Ton (CY07$) versus Arc-permeability (percent)

C. END-COST

The first and fifth GD/EB ship *End-cost* less *Other* per long ton (CY07$) versus *Internal Density* (pounds per cubic foot) are shown in Figure 16. The first and fifth GD/EB ship *End-cost* less *Other* per long ton (CY07$) versus combined Operations Compartment & Engine Room *Arc-permeability* (percent) are shown in Figure 17. The combined effect of shipbuilder costs and GFE as represented by "End-cost less Other" continues to support the theory.

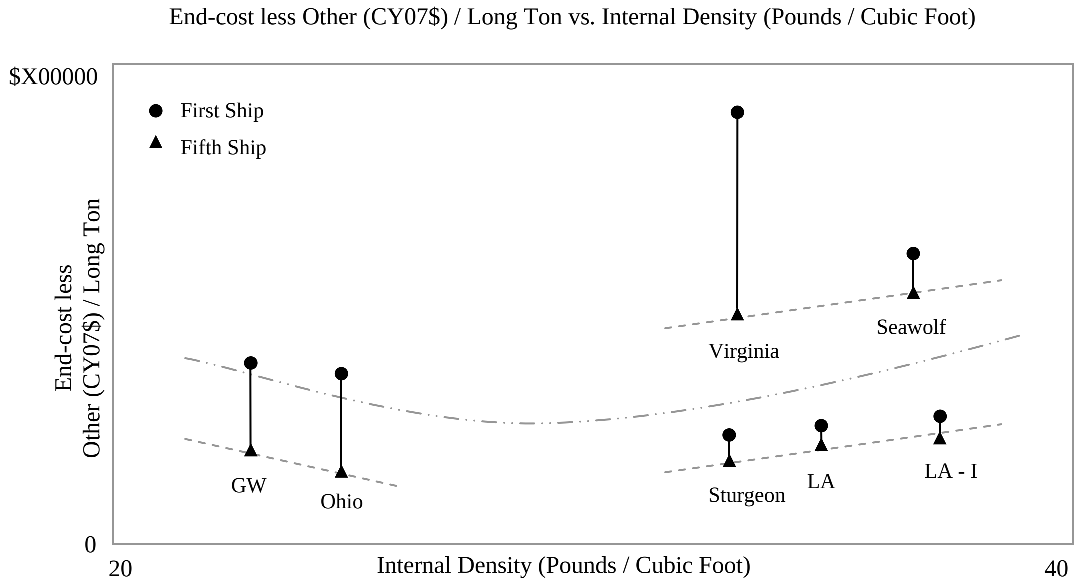


Figure 16. First and Fifth Ship End-cost Less Other per Long Ton (CY07$) versus Internal Density (pounds per cubic foot)

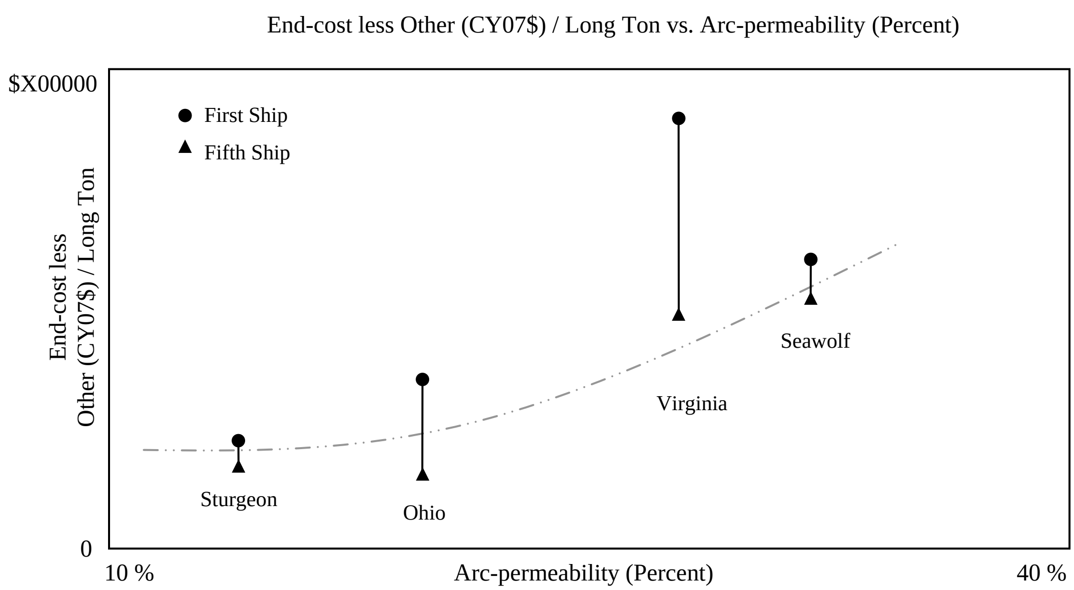


Figure 17. First and Fifth Ship End-cost Less Other per Long Ton (CY07$) versus Arc-permeability (percent)

D. DETAILED DESIGN HOURS

The detailed Design Hours per long ton (CY07$) versus *Internal Density* (pounds per cubic foot) are shown in Figure 18. The *Detailed Design Hours* versus combined Ops Compartment & Engine Room *Arc-permeability* (percent) are shown in Figure 19. The Ohio and Los Angeles Classes' data are shown—adjusted for differences in detailed design man-hours accounting methods previously mentioned. As suspected, increasingly dense designs require more time to design, which leads to increased costs. This is likely due to Tolerance stack-up, cascading changes, expensive corrections, the need for unique parts, etc.

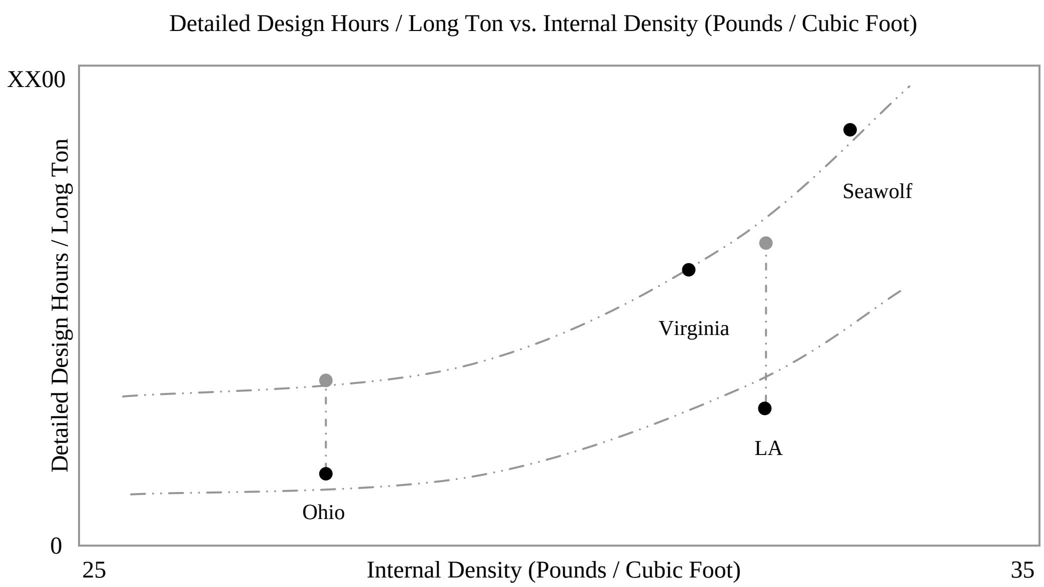


Figure 18. Detailed Design Hours per Long Ton (CY07$) versus Internal Density (pounds per cubic foot)

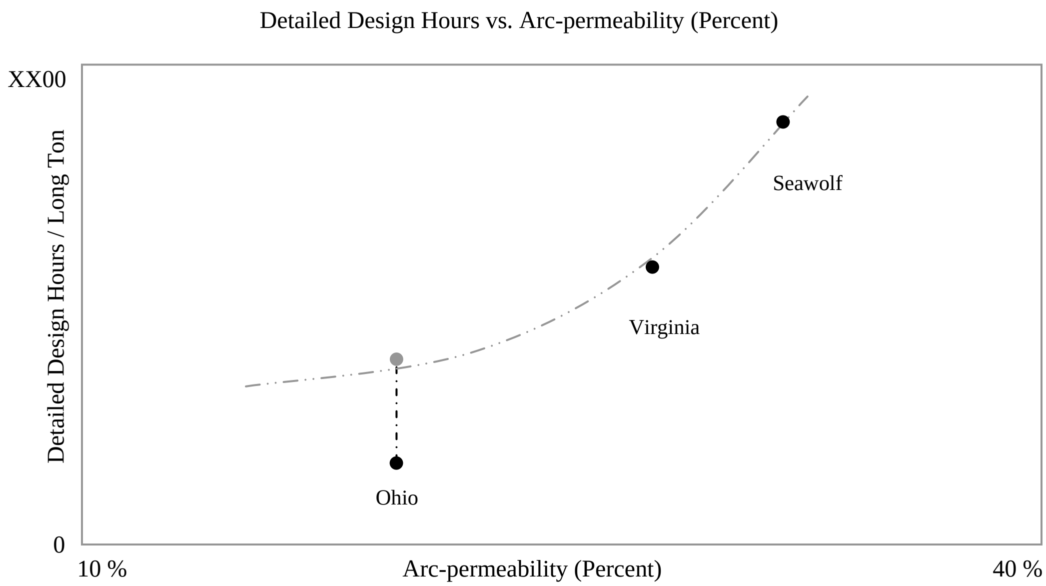


Figure 19. Detailed Design Hours versus Arc-permeability (percent)

E. PRODUCTION HOURS

The first and fifth GD/EB-built ship *Production Hours* per long ton versus *Internal Density* (pounds per cubic foot) are shown in Figure 20. The first and fifth GD/EB-built ship *Production Hours* versus combined Ops Compartment & Engine Room *Arc-permeability* (percent) are shown in Figure 21.

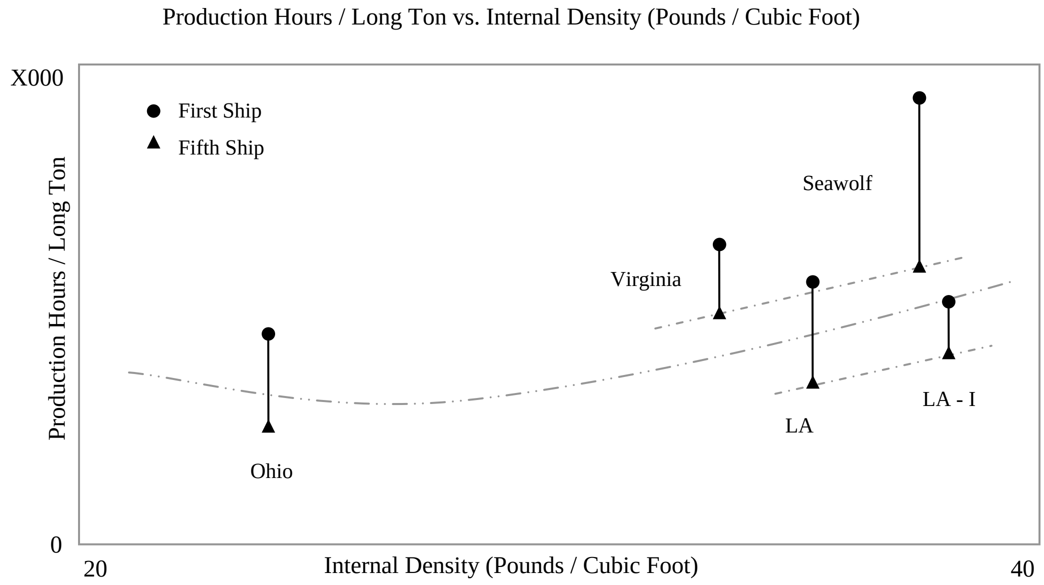


Figure 20. First and Fifth Ship Production Hours per Long Ton versus Internal Density (pounds per cubic foot)

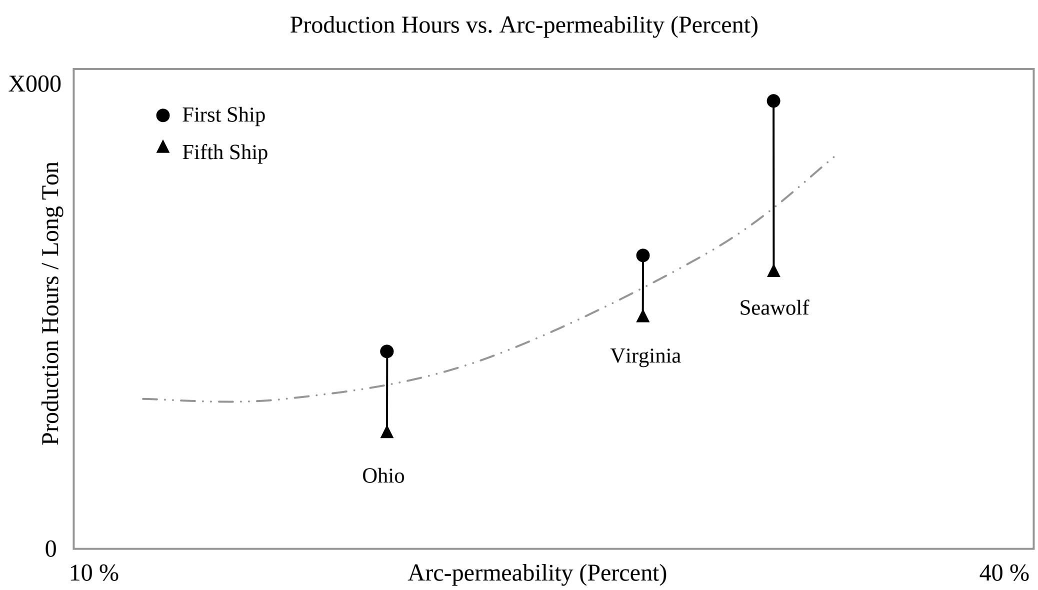


Figure 21. First and Fifth Ship Production Hours versus Arc-permeability (percent)

V. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY OF FINDINGS

1. Cost and Performance Risk are Asymmetric

The submarine diameter is fixed very early in any submarine design effort, which makes submarine length the only parameter that can be adjusted when volume increases are deemed necessary. Such design changes are costly, cause cascading effects and drive the submarine design away from its hydrodynamically optimal shape. Also, scarce volume leads to unanticipated increases in complexity, density and system interdependence—increasing the likelihood of a "first-of-class performance drop-off" and higher costs throughout the life cycle. For these reasons, the cost, schedule and performance risk associated with undercalling the eventual volume required to execute a successful submarine design is greater than the cost, schedule and performance risk associated with producing a submarine design that is ultimately deemed unnecessarily large.

2. Weight Reduction *Increases* Cost

The net effect of an overreliance on weight as a cost driver has led to the employment of weight and size limits as means to reduce costs, often producing the opposite effect. First, weight and size constraints encourage the use of unnecessary tolerances, unique parts, engineered materials, and weight-optimized designs. These tend to have a negative impact on life cycle costs. Second, the next 40 years of shrinking electronics—as predicted by Moore's Law—are unlikely to translate to an exploitable inventory of space and weight margins in the same way they have historically. Finally, adding global constraints to an already complex design effort limits the designer's ability to allocate the space and weight required to realize a cost-efficient design and to properly exploit the advantages provided by modular systems and construction methods, open architecture and commercial off-the-shelf products.

3. Density and Cost Exhibit a Family of U-shaped Curves

Internal Density and Arc-permeability reveal a U-shaped relationship between density and cost. Instead of one curve, a family of curves is assumed. Submarine designs will occupy a particular curve based on the combined effect of design specification, production rate and acquisition environment. Increased capability, reduced production rate and a less favorable acquisition environment will cause the density/cost curve to shift upward. Opposite trends will cause the curve to shift downward. Weight-optimized designs will result in submarine densities that will incur costs above minimum attainable according to the density versus cost theory. The Virginia Class design effort was a step in the right direction, but downward pressure on weight and size prevented it from reaching the optimal density corresponding to the opportunity for lowest costs.

4. Density Management Alone will not Reduce Costs

A determination to manage density as an indirect means to manage cost is the wrong conclusion to draw from the density/cost relationship. Such a simplistic approach will lead to all the undesirable behavior and cost outcomes observed when weight or size has been managed as an indirect means to cost. Appropriate conclusions to be drawn from an understanding of the density/cost relationship are discussed in the following section.

B. CONCLUSIONS

1. For the Program Head

Density measurements, to include Internal Density and Arc-permeability, provide the means to develop compensated gross tonnage (*cgt*) factors for naval vessels. Without a means to compare ships of various sizes and levels of complexity, one cannot say with any certainty if acquisition programs are increasingly broken or improving. Better analogies lead to more defendable cost estimates, more predictable outcomes and an increased understanding of the true state of a program. Better analogies also reveal which product and process improvements are producing their desired effect.

2. For the Cost Estimator

An analysis of density as it relates to cost reveals the asymmetric pressure initial sizing decisions exert in terms of cost and performance risk and the pressure that density exerts on the ultimate cost per unit weight of a design. A design that is deemed “too small” for its contents was more costly to design, construct, change, maintain and upgrade. It is inherently inflexible and may mandate unacceptable capability concessions. A design that is deemed “too big” for its contents was simpler to design, construct, change, maintain and upgrade. It is more flexible, and the penalties in speed, acceleration and overall performance are likely acceptable.

3. For Congress and the Secretariat

Adding constraints such as weight limits to an already complex design effort as a means to reduce costs will likely produce the opposite effect. Cost-estimating models and algorithms only allow the cost estimator to perform cost estimates more expeditiously. The parameters used in parametric cost estimates should not be extracted and managed as an indirect means to manage cost. As complex and interdependent the interactions between a vessel and its contents are, any arbitrary constraint can only serve to artificially and unnecessarily limit the ability of designers to achieve the best design from a performance per life cycle cost perspective.

4. For the Program Executive

A deliberately crafted, clearly stated and carefully guarded acquisition strategy and systems engineering approach must exist throughout each procurement effort if lower costs are to be realized. Such a clear vision can only be maintained by a single empowered individual who is solely responsible for the ultimate success or failure of the procurement process as a whole. No design size, production rate, vendor base, level of competition or even design density should be viewed as inherently low cost. Recall that product and process improvements can typically be exploited in only one of the following ways:

1. Increase the amount of capability in the same volume,
2. Reduce the volume required to offer the same capability, *or*
3. Provide the same capability in the same volume at a lower cost.

Density trends show that well-intentioned individuals acting independently will err towards one and two over the third. Therefore, if lower costs are the goal, the acquisition strategy must explicitly demand cost savings be extracted as each cost-saving opportunity presents itself.

5. For the Design-Build Team

Density reduction may represent a low-cost means to achieve the right mix of design flexibility, capability, reliability and maintainability from a life cycle cost perspective. The deliberate and aggressive implementation of space and weight margins may be necessary to ensure a submarine can remain relevant throughout the design life of its hull as rates of technological change and volatility in the threat environment dictate the need for increased flexibility in future submarine designs. Additionally, the potential cost effectiveness of a less dense design gives the lifecycle cost advocate a powerful voice. Finally, the cost-saving potential and flexibility of modular designs, open architecture systems and commercial off-the-shelf products are realizable only when given adequate space for their proper implementation.

C. RECOMMENDATIONS

This research effort served to reveal the growing inadequacies of weight-based cost-estimating techniques and the undesirable secondary effects that are likely when cost drivers are managed as an indirect means to manage cost. Perhaps for the first time, a relationship between submarine density and cost was demonstrated showing that density may indeed represent a previously underemphasized, if not unexplained, driver of historic submarine cost-growth in excess of inflation.

Much more could be done to prove the concept of density as a cost driver and to further quantify the results. The following are recommendations for further research that could build on the theoretical bases and preliminary conclusions contained herein.

- Derive compensated gross tonnage (*cgt*) factors for military ships and submarines.
- Further explore and attempt to quantify the relationship between submarine density and cost.
- Consider additional means of measuring submarine density.
- Develop density measurements for military surface ships, aircraft and vehicles.
- Evaluate space and weight margin policies and consider their continued relevance in an environment of increasing uncertainty and technological change.

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APPENDIX A. INTERVIEW QUESTIONS

Subject: Questions in support of thesis research.

Area of Research: Density as a cost-driver in naval submarine design and procurement.

Questions:

1) In your view, what have been the primary sources of ship/submarine cost escalation for the past several decades?

2) How has the complexity of submarines evolved? What metrics do you think capture best the evolution in the complexity of submarines (e.g., power generation, weapons onboard, number of support equipment, area of regard, LSW, power density, size, other)?

3) In your opinion, are there any design specifications, tolerances, constraints and/or design philosophies that tend to drive up the cost of submarines without a corresponding and adequate increase in safety, capability or reliability?

4) Can you cite any specific examples/studies in which a larger submarine component could be designed and produced more affordably than a comparably functioning component whose only difference is that it has been scaled down in size and/or customized to fit in a particular location?

5) Are there any disincentives in how the government procures ships/submarines that may lead to cost growth? Are there any initiatives that the government can encourage to reduce the cost of future ships (e.g., multiyear acquisition, lean production, open architecture, modularity, contractual incentives for cost reduction)?

6) Should more or less effort/investment be made into designing ships and submarines that are capable of adapting to the technological advances and migrating threats of the future? How do you balance such investment with the necessary sacrifices in current capability that would accompany such investment?

7) In your opinion, what is the best measure for submarine design density/congestion/complexity?

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APPENDIX B. P-5 BUDGET EXHIBIT

UNCLASSIFIED
CLASSIFICATION

P-5 EXHIBIT
FY20__ [PRESIDENT'S, FMB, or OSD/OMB] BUDGET E

APPROPRIATION: SHIPBUILDING AND CONVERSION, NAVY

PROGRAM COST BREAKDOWN (EXHIBIT P-5)

BUDGET ACTIVITY: P-1 ITEM NOMENCLATURE: SUBHEAD:

	FY 20__		FY 20__		FY 20__	
ELEMENT OF COST	QTY	TOT COST	QTY	TOT COST		TOT COST
PLAN COSTS	0	0	0	0	0	0
BASIC CONSTRUCTION/CONVERSION		0		0		0
CHANGE ORDERS		0		0		0
ELECTRONICS		0		0		0
PROPULSION		0		0		0
HM&E		0		0		0
OTHER COST		0		0		0
ORDNANCE		0		0		0
ESCALATION		0		0		0
TOTAL SHIP ESTIMATE		0		0		0
LESS: ADVANCE PROCUREMENT FY 20XX		0		0		
LESS: ADVANCE PROCUREMENT FY 20XX		0		0		0
NET P-1 LINE ITEM (REQUIREMENT)	0	0	0	0	0	0

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   Washington Navy Yard, Washington, DC

8. Wayne Rickter
   NAVSEA 05U Advanced Submarine Concepts Division
   Washington Navy Yard, Washington DC.

9. RADM Kevin McCoy
   NAVSEA Chief Engineer
   Washington Navy Yard, Washington, DC

10. The Honorable Douglas Brook
    Assistant Secretary of the Navy (FM&C)
    Pentagon, Washington, DC

11. RADM Stanley Bozin
    Director, Office of Budget
    Pentagon, Washington, DC

12. Wendy Kunc
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